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Late Cretaceous and Tertiary Burial History, Central Texas

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ABSTRACT

In Central Texas, the Balcones Fault Zone separates the Gulf Coastal Plain from the elevated Central Texas Platform, comprising the Hill Country, Llano Uplift, and Edwards Plateau provinces to the west and north. The youngest geologic formations common to both regions are of Albian and Cenomanian age, the thick, widespread Edwards Limestone, and the thin overlying Georgetown, Del Rio, Buda, and Eagle Ford–Boquillas formations. Younger Cretaceous and Tertiary formations that overlie the Edwards and associated formations on and beneath the Gulf Coastal Plain have no known counterparts to the west and north of the Balcones Fault Zone, owing mostly to subaerial erosion following Oligocene and Miocene uplift during Balcones faulting, and secondarily to updip stratigraphic thinning and pinchouts during the Late Cretaceous and Tertiary.

This study attempts to reconstruct the burial history of the Central Texas Platform (once entirely covered by carbonates of the thick Edwards Group and thin Buda Limestone), based mostly on indirect geological evidence:

(1) Regional geologic maps showing structure, isopachs, and lithofacies;
(2) Regional stratigraphic analysis of the Edwards Limestone and associated formations demonstrating that the Central Texas Platform was a topographic high surrounded by gentle clinoform slopes into peripheral depositional areas;
(3) Analysis and projection of regional updip thinning patterns of Upper Cretaceous and Tertiary formations from the Gulf Coast Basin northwestward along the San Marcos Arch, across the Balcones/Ouachita Downwarp, into the heart of the Central Texas Platform;
(4) Derived published stratigraphic analyses of the Cretaceous Western Interior Seaway;
(5) Estimation of burial depth from thermal maturity of Eagle Ford organic shales (overlying the Edwards by approximately 150 feet) in the outcrop area around Austin and Comstock, and in the subsurface of Wilson, Karnes, and DeWitt counties; and
(6) Implications as to burial depth of Edwards and associated formations based upon the presence or absence of stylolites, which form in carbonate rocks under known subsurface conditions, including depth related to pressure.

The Late Cretaceous through Tertiary geologic history of the Central Texas Platform may be summarized as follows:

(a) Over the ~10 million years following the end of the Albian, the vast Edwards carbonate bank was mantled beneath a covering veneer of thin (<100 feet) early Cenomanian formations (Del Rio, Buda, and Eagle Ford–Boquillas) that did not eliminate the gentle depositional topography around the bank margins, and also did not cover some local highs along the bank margins.
(b) The western interior of the Central Texas Platform was covered by 700 to 1100 feet of open marine Austin Chalk (Santonian), Taylor Clay, and Navarro Marl (Campanian and Maastrichtian), and Midway Clay (lower Paleocene), which muted but did not obliterate depositional topography of the covered bank margins. The low-lying muddy bank was periodically exposed during this ~28 million year period, and meandering streams developed along its margins with surrounding very shallow pelagic seas.
(c) Upper Paleocene, Eocene, and Oligocene formations pinched out preferentially westward and northward onto the Balcones/Ouachita Downwarp, which coincided with the underlying Ouachita Thrust Belt and the future Balcones Fault Zone. Throughout this period (~37 million years), the exposed, low-lying bank (adjacent to coastal plain and fluvial-deltaic depositional tracts) began to be gently uplifted. This allowed subaerial erosion to begin, of surficial Eocene sediments as well as the mantle of lower Paleocene and Upper Cretaceous soft mudrocks and marls. Gradual entrenchment of incised streams around the bank margins also occurred.
(d) Beginning in late Oligocene time, the combination of accelerating gulfward downwarping and uplift of the

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interior resulted in increased exposure and erosion of the buried Central Texas Platform, until Georgetown and Edwards rocks began to be exposed and eroded, their detritus deposited in alluvial aprons on the adjacent coastal plain. Balcones faulting during the late Oligocene and Miocene (~23 million years) marked the culmination of uplift along the west and north side of the Balcones Fault Zone, and accelerated incision of existing streams, especially around the margins.

(e) **Continued regional uplift of the Colorado Plateau during late Miocene and Pliocene (~8 million years) elevated the western margins of the exposed Edwards carbonate bank, tilting the Plateau surface gently toward the southeast. Headward erosion from east and south began to cut into the high-standing carbonate mass. Streams feeding outward from the Plateau constructed sloping gravel aprons composed of carbonate and chert debris onto the coastal plain. So far, approximately 9300 cubic miles of rock has been eroded from the Edwards Plateau, Llano Uplift, Hill Country, and upper Gulf Coastal Plain as the result of Tertiary uplift and Balcones faulting, with such erosion continuing today.**

PREFACE

I began my investigations of the Edwards Group of Texas in 1962, when I was a young geologist working for the Shell Oil Company in South Texas, sitting wells on the so-called Edwards Reef Trend (= Stuart City Reef), and the backreef Person-Fashing Fault Trend a dozen miles updip to the northwest. In 1966, I returned to the University of Texas (Austin), where my Ph.D. dissertation was a regional monograph integrating what I had learned about the Edwards in the subsurface (released courtesy of Shell), with results of my 1967 surface mapping of Edwards rocks in the eastern Edwards Plateau (Rose, 1972). During the same period Shell geologists C. I. Smith, Jr. and Johnnie B. Brown, under the leadership of the late Frank Lozo, were carrying out extensive stratigraphic investigations of outcropping Edwards and equivalent formations farther west and north, but this superb work, which facilitated the stratigraphic integration of Edwards and equivalent formations of the entire region, remained mostly proprietary until publication by the Texas Bureau of Economic Geology (Smith et al., 2000).

As the dissertation approached completion, I was fascinated by new questions about the Edwards Plateau, especially the geologic events that occurred after deposition of the widespread, pelagic Buda Limestone, at the end of the Comanche Epoch. What was the Late Cretaceous and Tertiary history of the Plateau area? How deeply had the Edwards been buried by younger formations in the Plateau area? Was it subaerially exposed during the Late Cretaceous? The Early Tertiary? Or was it finally exposed and eroded only during and after uplift by Balcones faulting during the late Oligocene and early Miocene? Other questions concerned the entire immense carbonate bank complex that formed in West, Central, and South Texas, in the lee of the Stuart City Reef—how did it relate to extensive Lower Cretaceous terrigenous clastics of the Rocky Mountain Province? How did the Comanche carbonate shelf relate to the Cretaceous Western Interior Seaway?

Addressing these geological questions was hampered by three basic problems: (a) most of the pertinent research was proprietary or still to be carried out; (b) Post-Edwards rocks were mostly absent in the region, either by non-deposition or later erosion, so there was very little direct evidence bearing on the problem[1]; and (c) I was deeply involved in a professional career, with little time to spend on personal investigations. So I put further research on the Edwards Plateau on the shelf for nearly 40 years.

I finally returned to these long-deferred questions in 2012, 50 years since I first began to study the Edwards, and 40 years after publication of Rose (1972). There is still much that remains unknown about these topics, but we do have more relevant data now, and they allow us to make reasonable inferences about what may have happened in Central and West Texas during the ~90 my from the Late Cretaceous through the Pliocene, after Balcones faulting elevated the southeastern margins of the Edwards Plateau during the late Oligocene and early Miocene. The present report thus addresses research questions that I have puzzled over for many years.

INTRODUCTION

The Edwards Plateau is an immense tableland that dominates the geography of West-Central Texas, covering more than 45,000 square miles, in parts or all of 29 counties (Fig. 1). Along its northern margin, the Plateau rises 100 to 300 feet above the adjacent rolling prairies; along its southern margin, it stands 500 to 1500 feet higher than the adjacent coastal plains of the Rio Grande Embayment. To the east, where the Plateau is dissected by east-flowing rivers, high-standing divides rise 100 to 400 feet above valleys cut in older formations. Erosional remnants of thin, deeply weathered Buda Limestone overlie the Edwards in flat, high divides in the heart of the Plateau. The Edwards Plateau extends westward across the Pecos River, where it is sometimes called the Stockton Plateau, and to the southwest, across the Rio Grande, where it is known as the Serrania del Burro, which owes its much higher elevation to Laramide uplift. To the northwest, the upper surface of the Edwards Plateau merges almost imperceptibly with the younger High Plains (or Llano Estacado) of West Texas and the Texas Panhandle (Rose, 2012).

The Plateau is the topographic and geomorphic expression of a thick, widespread, flat-lying sequence of Lower Cretaceous (mostly middle and upper Albian) limestones and dolostones assigned to the Edwards Group, which thickens southwestward, from about 400 feet on the north to more than 800 feet along the southern edge of the Plateau. Edwards carbonate strata are generally harder and more resistant to weathering and erosion than the underlying softer, Trinity-age sandstones and marls, which is why the Edwards Plateau is a high-standing topographic feature, dissected and rough-edged around its margins (Rose, 2004).

Neogene erosion of the eastern Edwards Plateau region, related to Balcones faulting and uplift, has stripped away much of the Edwards Group from alluvial valleys cutting eastward and southward across Trinity-age Glen Rose and Hensel formations, leaving only Edwards remnants in high-standing interfluvial divides. This distinctive landscape is known as the Texas Hill Country. In the valleys of the Colorado River and its east-flowing tributaries, the Pedernales, Llano, and San Saba rivers, erosion has cut down into Paleozoic and Precambrian rocks of the Llano Uplift. But prior to Balcones faulting, a continuous blanket of Edwards (and Buda) strata covered the entire Central Texas Province, including that part which is now in the subsurface (Woodruff, 2002).

Edwards carbonate rocks record deposition on a vast offshore bank, far south and west of any substantial input of terrigenous sands, muds and clays. The climate was subtropical, temperate to arid. Depositional environments ranged from re-

[1]Actually, only a very thin (<40 ft) veneer of Buda strata overlies the Edwards over much of the Edwards Plateau, with even thinner remnants of underlying Del Rio pinching out on the southern flank, and overlying Boquillas (= Eagle Ford) present in the central and southwestern sectors. Southward-thickening erosional wedges of Austin Chalk are present on the far southern flank of the Edwards Plateau, where it impinges on the Chihuahua Trough. Otherwise, there are no Upper Cretaceous or Tertiary formations present in the region, except for scattered Pliocene/Pleistocene high gravels around the Plateau margins, and Quaternary alluvial deposits in some river valleys.

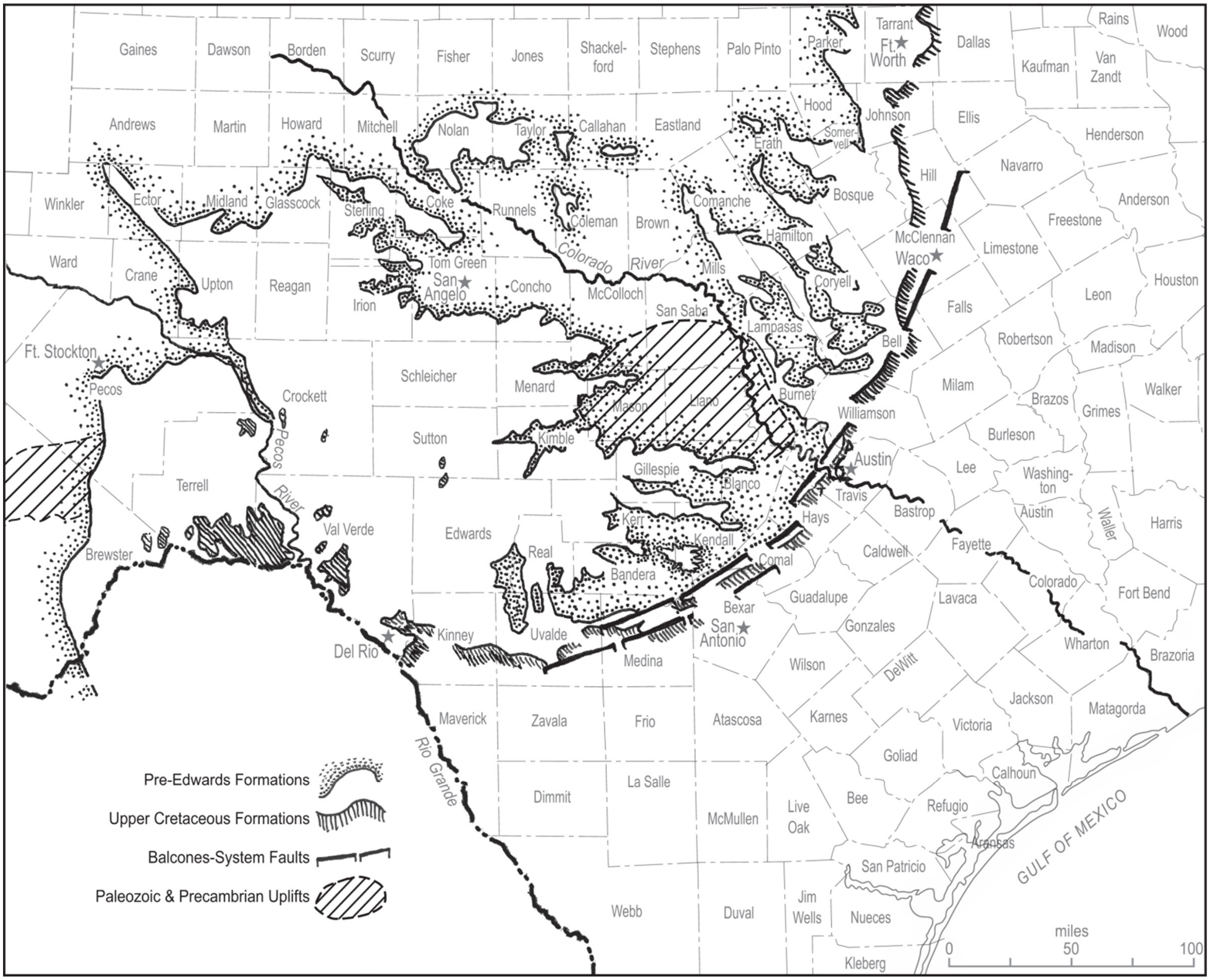


Figure 1. Edwards Plateau, Llano Uplift, Hill Country, Balcones Fault Zone, and Coastal Plain, Central Texas.

stricted shelf interior, to low-energy shallow open shelf, to high-energy bioclastic shelf-margin. Where such environments of deposition survived into latest Albian time (typically high on the Central Texas Platform), the sedimentary rocks that formed there are also called "Edwards," even though they are coeval with uppermost Georgetown strata to the south and northeast (Rose, 1972; Young, 1974, 1986).

A large body of well-documented geologic research has been carried out on the Edwards Group in the Edwards Plateau region over the past 50 years. But little has been written about the subsequent geologic history of the region after Edwards deposition ended—i.e., what younger formations may have covered the Edwards, their thickness and areal extent. We understand that the eastern and southern margins of the Edwards Plateau were elevated above the Gulf Coastal Plain beginning about 25 million years ago, during late Oligocene and early Miocene time, by Balcones faulting (Weeks, 1945a, 1945b). This event left unmistakable sedimentary evidence—a widespread carbonate and chert gravel-and-sand outwash plain—in Oligocene Catahoula and Miocene Oakville outcrops on the Gulf Coastal Plain to the east and southeast, representing alluvial and coastal plain deposits derived from recently uplifted, rapidly eroding carbonate uplands to the west and northwest. It is generally accepted that the gentle gulfward tilt of the Plateau is post-Miocene, related to the regional rise of the Colorado Plateau to the northwest (Galloway et al., 2011). Otherwise, the geologic timing of Edwards Plateau uplift remained unknown—was the Plateau subaerially exposed, weathered, and eroded beginning sometime in the late Cretaceous, or during the Eocene, or only incidental to Balcones faulting and uplift in the Oligocene and Miocene?

Purpose

The purpose of this paper is to summarize the geologic events that may have transpired between the emergence of the immense Edwards carbonate bank in the late Albian/early Cenomanian (100–98 million years ago), and the Pleistocene, especially how those events influenced the burial history of Edwards and associated formations. Because of the general absence of conventional geologic evidence in the subject area, such an undertaking has required consideration and synthesis of many geologic subspecialties—stratigraphy, tectonics, burial history, paleogeography, organic geochemistry, petrology, and porosity/permeability analysis—to piece together various lines and items of evidence to construct a credible, though admittedly speculative, geologic history of this large region over the last ~100 million years (since the end of Edwards deposition).

Pertinent Previous Work

Cretaceous rocks of the Edwards Plateau region are now well understood, thanks to careful, well-documented geologic mapping and stratigraphic syntheses, mostly by geologists involved with sustained efforts by the late Frank Lozo of Shell Development Co.: Lozo and Smith (1964), Moore (1967), Smith (1970), Rose (1972, 1986a), Halley and Rose (1977), Smith and Brown (1983), Miller (1984), and Smith et al. (2000). Such work provided the necessary stratigraphic framework for many subsequent diverse and detailed research projects.

Research projects on equivalent formations in the subsurface of central and south Texas generated counterpart mapping, stratigraphic correlation and geologic synthesis: Winter (1961), Tucker (1962), Bebout and Loucks (1974), and Rose (1986b).

Beginning in 1961, Lozo and Smith (1964) and Smith et al. (2000) mapped, correlated and synthesized the Fredericksburg and Washita stratigraphic succession from the central Edwards Plateau westward across Trans-Pecos Texas, and southward, into the Maverick Basin. Smith (1970) carried this sequence across the Big Bend region and into the Serrania del Burro of northern Coahuila, Mexico. Rose (1972) mapped and correlated Edwards and associated formations of the subsurface with their outcrop counterparts of the Balcones Fault Zone and eastern Edwards Plateau, connecting with the findings of Lozo and Smith, thus completing a complete stratigraphic synthesis of these formations across Central and Southwest Texas. Young (1974, 1986) reported on ammonite zonations that confirmed the physical stratigraphic correlations of Tucker (1962) and Rose (1972). Surface mapping of the entire Edwards Plateau region was provided by the Texas Bureau of Economic Geology's mammoth 1:250,000 Geologic Atlas of Texas, including the Austin (1974), Del Rio (1977), Fort Stockton (1982), Llano (1981), Pecos (1975), San Angelo (1976), San Antonio (1983), Seguin (1974), Sonora (1981), and Waco (1970) sheets.

Analogous regional mapping and stratigraphic research were also being carried out at about the same time to the north, in the broad area of the middle Cretaceous North American Interior Seaway, by many different geologists. Two especially pertinent papers were a regional synthesis by Kauffmann (1977), and a synthesis of middle Cretaceous stratigraphy in southeastern Colorado, southwestern Kansas, northeastern New Mexico, and the Oklahoma Panhandle by Scott (1977). In 2003, Scott et al. published an integrated Albian-lower Cenomanian stratigraphic synthesis of sedimentary formations of the North Texas–Tyler Basin, the basinal area northeast of the Edwards Plateau. Phelps et al. (2014) published a comprehensive paper synthesizing the Cretaceous stratigraphy of the Texas Gulf Coast, focusing on sequence stratigraphy.

In 1975, Princeton University press published the Stratigraphic Atlas of North America, an extraordinarily comprehensive series of isopach, subcrop, and lithofacies maps, with accompanying cross-sections, prepared by the Exploration Department of Shell Oil Company, and edited by T. D. Cook and A. W. Bally. I have used this as a source for most of the isopach mapping of Upper Cretaceous and Tertiary formations included herein.

Papers addressing the structural geology of Central Texas, including the Edwards Plateau, the subsurface Ouachita Fold Belt, the Balcones Fault Zone, and the subsurface of the inner Gulf Coastal Plain, include: Weeks (1945a, 1945b), Flawn et al. (1961, 1967), Murray (1961), Grimshaw and Woodruff (1986), and Ewing (1991, 2003, 2005).

The Cenozoic history of the Gulf of Mexico Basin was published by Galloway et al. (2000), and a comprehensive synthesis of Cenozoic stream drainage systems feeding into the Gulf basin was published by Galloway et al. (2011). A recent series of publications by Jackson et al. (2011), Hudec et al. (2013), and Dooley et al. (2013) related offshore salt movements in the deep Gulf of Mexico to Tertiary tectonics in the northern margins of the onshore Gulf.

REGIONAL STRUCTURAL ELEMENTS AND HISTORY

The structural-geologic history of Central Texas is long and complex. Fig. 2 shows structural features that are important to the geologic history of Central Texas in general, and the deposition of Cretaceous and Tertiary formations, in particular.

Ouachita Structural Belt

In North and Central Texas the Ouachita Structural Belt, comprehensively described by Flawn et al. (1961), lies entirely in the subsurface. It passes from near Dallas southwesterly to the Austin area, then begins its westward swing, under San Antonio and Uvalde. It is interrupted by the late Paleozoic Devils River Uplift near Del Rio, then bears northwesterly and finally westerly into the area of the Marathon Dome (Laramide), West Texas, where it comes to the surface. The Ouachita Structural Belt is generally thought to be the result of a late Paleozoic continental collision. It consists of a western/northern frontal zone of Appalachian-style folds and thrust faults involving Paleozoic rocks through middle Pennsylvanian, and an eastern/southern metamorphic zone, of uncertain age and origin. In the subsurface, the Ouachita Structural Belt lies buried beneath upper Jurassic and lower Cretaceous sedimentary rocks, and appears to "wrap around" the Llano Uplift.

Central Texas Platform

The Central Texas Platform is the term given to the broad, structurally positive cratonic area comprising the Texas Hill Country, Llano Uplift, and Edwards Plateau, west and north of the Balcones Fault Zone. This regional structural feature also has a paleogeographic component: it coincides with the presence of mostly clay-free Albian carbonate lithofacies characteristic of shallow-marine to restricted shelf-interior depositional environments.

Llano Uplift

The Llano Uplift, a Precambrian-cored positive domal feature located mostly in Llano, Mason, San Saba, Gillespie, and Blanco counties, seems to have served as a long-time structural buttress for younger geological trends. Structural contours on top of Precambrian basement (Fig. 3) dip gently away in all directions from the center of the Llano Uplift. Dip is steepest to the northeast, east, southeast, south, and southwest; areas of most gentle dip lie to the west, northwest, and north.

The domal nature of the Llano Uplift was maintained through the lower Paleozoic (Fig. 4), as shown by structural contours on top of the Lower Ordovician Ellenburger Group, which dip gently westward into the Midland Basin, northward into the Fort Worth Basin, steeply eastward toward (and beneath) the buried Ouachita Structural Belt, and steeply southward into the Kerr basin (also beneath the Ouachita Structural Belt). The steep structural downwarp off the east and south flank of the Llano Uplift—also noted above on top of Precambrian basement—is again present at top Ellenburger.

Radial dip away from the Llano Uplift, so prominent in the preceding Precambrian and lower Paleozoic structure maps, has by base Cretaceous (Fig. 5) been modified. Steep dip to the east and south (into the subsiding Gulf Coast Basin) is still present, but is less steep than on the underlying lower mapping datums. Dip of the base Cretaceous to the north, over the Paleozoic Bend Arch (Cheney, 1918; Ewing, 1991) is essentially flat, whereas the base Cretaceous datum rises gently but steadily to the west and northwest, reflecting regional uplift of the Colorado Plateau.

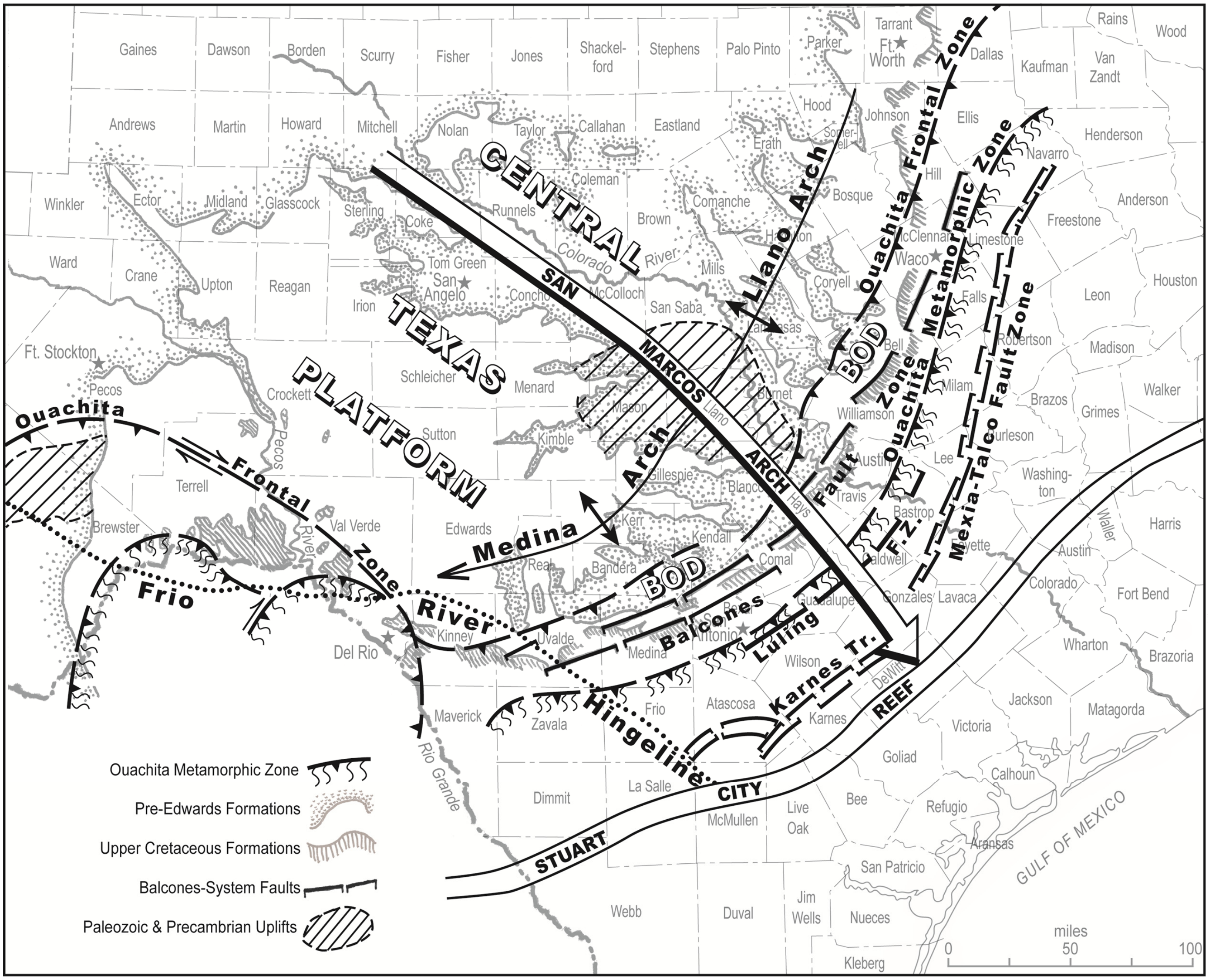


Figure 2. Regional structural elements, Central Texas. BOD, Balcones/Ouachita Downwarp.

Restored structure on top of the Edwards and associated limestones (Fig. 6) allows integration of surface and subsurface mapping throughout the region. Where erosion in the eastern Edwards Plateau and Hill Country has removed parts or all of the upper Edwards, the original thickness has been restored by adding Edwards isopachous values (derived from the subsurface and from the central and western parts of the Edwards Plateau, where the complete Edwards section is present) to the base Edwards of Rose (1972, 1986a, 2004). The mapped surface approximates the surface of the Edwards Plateau at the end of Balcones faulting and uplift. Northwest of the Llano Uplift, the base of the Edwards rises gently (~10 feet per mile) but steadily toward the northwest, reflecting regional Miocene/Pliocene uplift of the Colorado Plateau. This is the same configuration observed in the eastward-sloping Ogallala Formation of the High Plains (Llano Estacado), believed to have formed at the same time (Ewing, 1991). The previously noted zone of steepening dip on the east, southeast and south sides of the Llano Uplift is still present at this mapping horizon

Two structural closures are apparent, a smaller feature in northwestern Kimble County which may be a shallow manifestation of deeper Paleozoic faulting and a more significant feature, a broad northeast-southwest anticline across southern Edwards, northern Real, central Kerr, and western Gillespie counties, having vertical closure of more than 250 feet. This is the Medina Arch of Rose (1972), which also forms the southwestern end of the Llano Arch of Ewing (2005). Paleostructural analysis suggests that the Medina Arch is a late-stage feature related to Balcones faulting. The previously noted zone of steepening dip around the east, southeast, and south side of the Llano Uplift is still apparent at the top Edwards mapping surface.

Balcones/Ouachita Downwarp

Importantly, the regional downwarp along the eastern, southeastern and southern margins of the Llano Uplift, previously noted on Figure 2, and all subsequent structure maps, is still present at top Edwards (Fig. 6), where it lies inboard (west and north) from, and above, the subsurface Ouachita Structural Belt. Dip rates eastward, southeastward, and southward from the Llano Uplift are consistently steeper on the deeper (older) mapping surfaces, and more gentle on the Cretaceous mapping datums. This indicates that this persistent regional flexure represents the northern margin of the Gulf of Mexico Basin. Following Ewing (1991, 2005) it will henceforth be referred to as the Balcones/Ouachita Downwarp. It is important because it represents the most likely zone where Upper Cretaceous and Tertiary formations thinned or pinched out around the northern (cratonic)

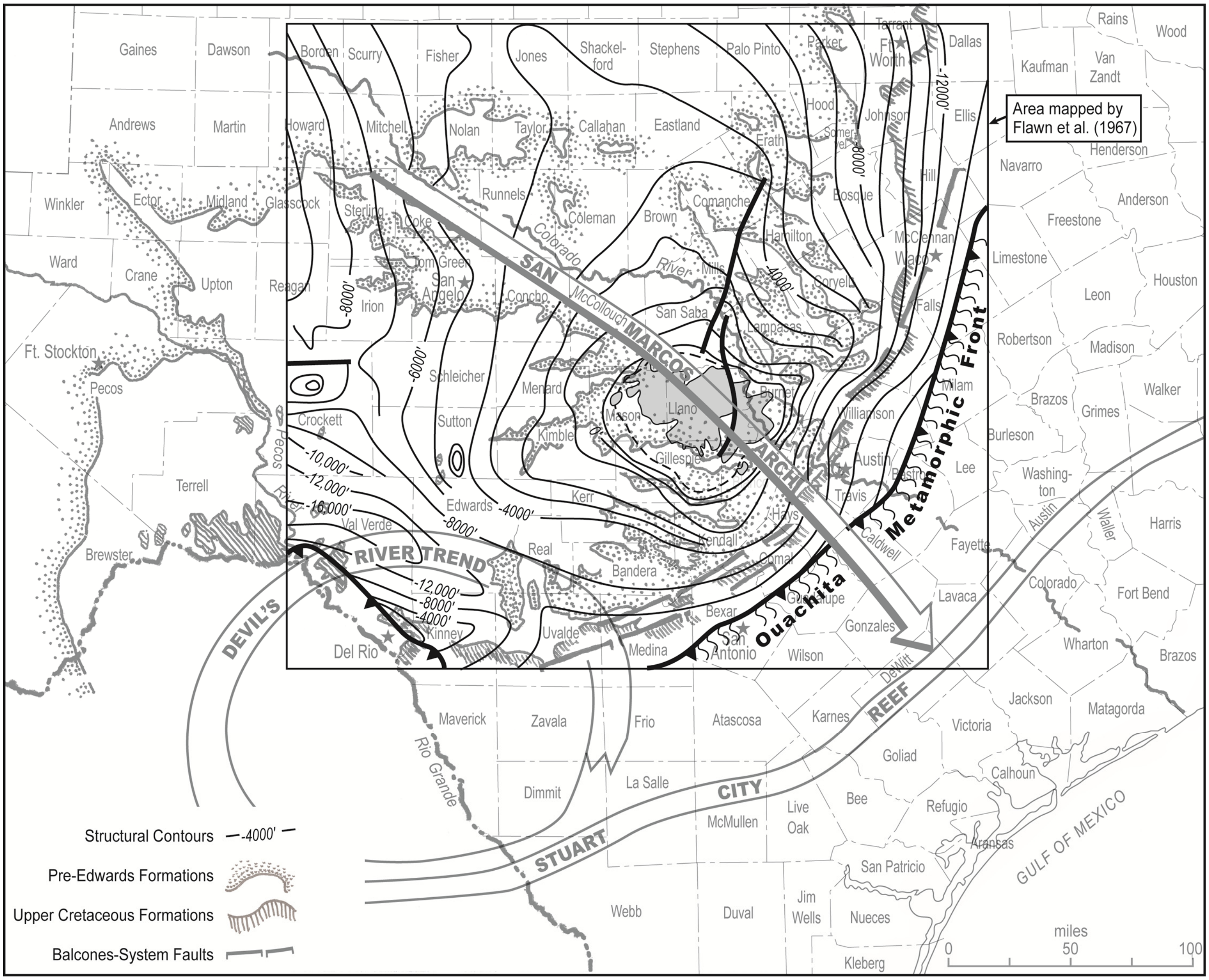


Figure 3. Structure on top Precambrian, Central Texas (after Flawn et al., 1967).

margin of the Gulf of Mexico. The "Gulf Coast Hinge Line" of Hudec et al. (2013) coincides with the Balcones/Ouachita Downwarp from the San Marcos Arch northward for about 75 miles before diverging eastward across the East Texas Basin.

San Marcos Arch

The structural axis of the Central Texas Platform is the San Marcos Arch, which extends southeastward from near Big Spring across the Llano Uplift, through San Marcos and Cuero. In the subsurface, structural and stratigraphic evidence of this axis does not seem to extend coastward beyond the vicinity of Victoria (Fig. 2). The San Marcos Arch acted as a persistent, gentle, positive structural axis affecting lithofacies and thickness patterns of the Edwards and associated formations, as well as Upper Cretaceous and Paleogene formations.

Frio River Hingeline

Smith et al. (2000) recognized a broad tectonic hingeline passing east-southeast from the Marathon Dome across northernmost Coahuila parallel to the Rio Grande, and back into Texas a few miles north of Del Rio, thence across northern Kinney County, central Uvalde County, and into northwestern Frio County: "South of [this] tectonic hingeline . . . rates of subsidence were faster, and the total [Cretaceous] section thickens. Over the Central Texas Platform positive area [to the north and east] the section is thinner."

Ewing (1987, 2003) identified the eastern part of the same flexure, where it influences the stratigraphy of subsurface Upper Cretaceous formations, calling it the Frio River Line (Fig. 2). The western end of this flexure merges with the westerly extension of the aforementioned Balcones/Ouachita Downwarp, together clearly forming the northern edge of the Rio Grande Embayment in Texas (Fig. 6) and, as it extends northwesterly, the northeastern margin of the Chihuahua Trough, which appears to reach northerly into New Mexico, where it connects with the Cretaceous Western Interior Seaway, as shown by maps of Kauffman (1977) and Scott (1977).

Balcones Fault Zone

The Balcones Fault Zone involves Mesozoic formations as well as the underlying Ouachita facies. It lies consistently above the Ouachita Structural Belt, midway between the leading overthrusted and folded zone and the trailing metamorphic thrust

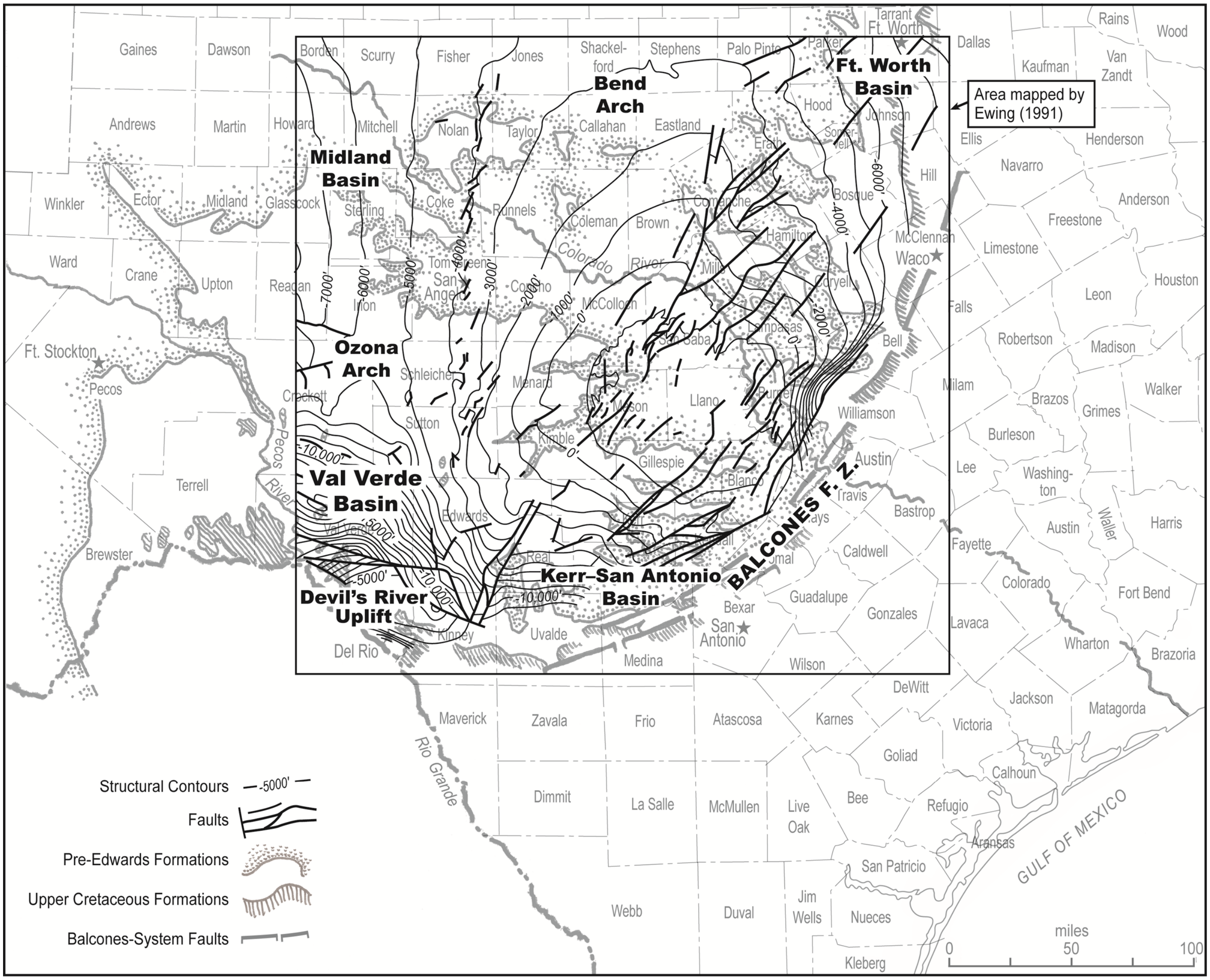


Figure 4. Structure on top Ellenburger Group (Lower Ordovician), Central Texas (from Ewing, 1991).

front (Fig. 2). It is also located midway along the trend of the Balcones/Ouachita Downwarp. Faulting is en echelon and mostly extensional, down to the southeast. The Balcones Fault Zone reaches maximum displacement around San Antonio, approaching 2000 feet, and extends northward through Austin and Waco, finally dying out around Hillsboro, a distance of about 200 miles. Southwest from San Antonio, the Balcones Fault Zone reaches about 150 miles, across Medina County, north of Uvalde, dying out east of Del Rio. It is consistently about 20 miles wide in the middle sector, narrowing toward each end as displacement diminishes. Ewing (2005) pointed out that, from San Antonio westward the major faults step to the right, whereas from San Marcos northward they step left. This generates a map pattern showing a southeast protrusion of the Edwards outcrop in the New Braunfels–San Marcos area, along the axis of the San Marcos Arch.

The relationship between the Balcones Fault Zone and the underlying Ouachita Structural Belt remains obscure; most authors (e.g., King, 1961; Murray, 1961) have simply described the Ouachita trend as a zone of weakness in the upper crust, thus a more likely site for later faulting. Ewing (2005) identified three possible origins: (1) reactivation of Ouachita thrusts and guide planes, (2) deeper Llano-style normal faults, or (3) keystone faults due to bending that dies out with depth. Hayman (2009) offered two alternate hypotheses: (1) uplift induced by sediment loading and (2) thermal subsidence models.

Time of Balcones faulting (and concurrent uplift of the eastern Edwards Plateau area) is generally accepted as late Oligocene and early Miocene, based on Edwards- and Georgetown-type pebbles, sand grains, and fossil fragments found in Catahoula and Oakville coastal-alluvial sediments in outcrops located about 80 miles coastward of the Balcones Fault Zone (Weeks, 1945a, 1945b; Ely, 1957; Ragsdale, 1960; Galloway, 1977). Galloway et al. (1982, 2000, 2011). Whether this indicates the beginning, peak, or end of Balcones faulting (and Plateau uplift) is not known. Today, the Balcones Fault Zone is widely considered to be dormant—Ewing (2005) pointed out that Pleistocene Uvalde and related gravels are not cut by Balcones faults.[2]

The Miocene age of Balcones faulting coincides with other structural events in the Cenozoic Gulf of Mexico as well as onshore on the North American Craton. Hudec et al. (2013) point out that the Jurassic Toledo Bend Flexure of East Texas was re-

[2]Other authorities, especially the U. S. Geological Survey, assign the Uvalde to the Pliocene. The writer follows U.S. Geological Survey usage.

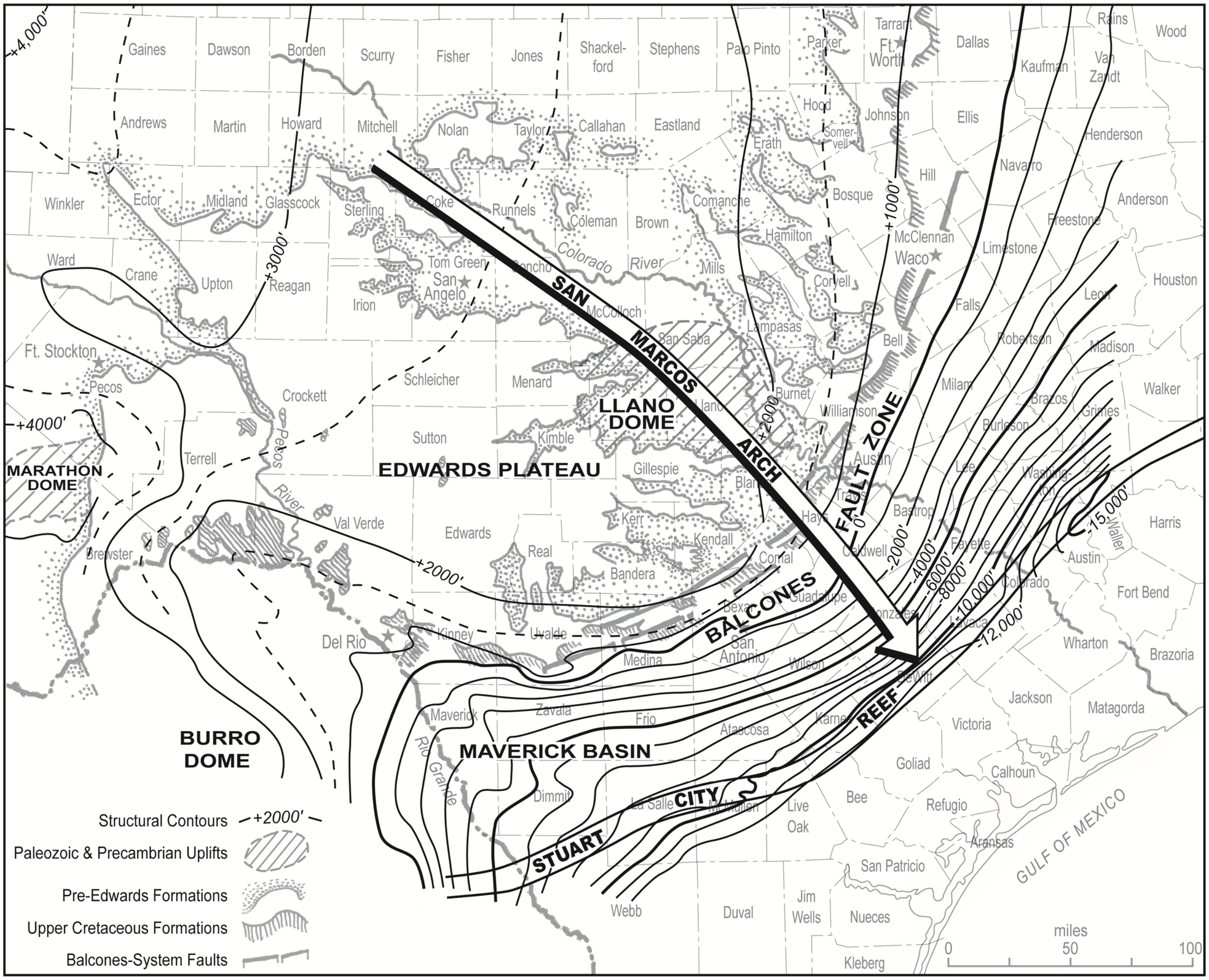


Figure 5. Structure on base Cretaceous (from Ewing, 2005).

activated in the Miocene. There is no structural connection, however, with the Balcones Fault Zone, or its antithetic counterpart, the Luling Fault Zone, although the western end of the Toledo Bend Flexure does appear to merge with the southwestern extension of the Mexia-Talco Fault Zone, which was active during the middle Cretaceous. Jackson et al. (2011) related enhanced salt movements that occurred in the deep Gulf of Mexico to uplift of the North American craton during the Oligocene and Miocene. Dooley et al. (2013) indicated that enhanced middle Miocene sedimentation in the Gulf of Mexico was related to uplift of the continental interior. Boettcher and Milliken (1994) presented compelling evidence for Miocene uplift of the southern Appalachians.

Other questions pertain to the relationship between Balcones faulting and the regional uplift of the Edwards Plateau—did Balcones faulting initiate or terminate Plateau uplift? Two lines of evidence suggest that it was the terminal—not the initiating—event:

(1) the presence of alluvial-deltaic and coastal-interdeltaic terrigenous clastic sediments in the upper Paleocene Wilcox Group, lying only about 20 miles coastward (southeast) of the Balcones Fault Zone, would seem to mandate that the Edward carbonate mass to the west was already elevated above late Paleocene sea-level at that time; and

(2) the consistent regional superposition of the Balcones Fault Zone along the Balcones/Ouachita Downwarp, a long-historied regional flexure, suggests a genetic relationship between them.

Furthermore, the absence of any widespread marine incursion in the otherwise coastal-alluvial lower Miocene succession of South-Central Texas (Galloway et al., 2000) indicate that net Balcones movement did not involve significant downward displacement of the coastal side of the fault. Accordingly, displacement of the upthrown block was not just relatively up—it must have been absolutely up (relative to Miocene sea-level).

Other Faults Involving Lower Cretaceous Rocks, Subsurface of South-Central Texas

Centered around the San Marcos Arch, and about 30 miles downdip (southeast) of the Balcones Fault Zone (and parallel to it) is the en echelon, apparently antithetic Luling Fault Zone (Fig. 2). Running from western Wilson County northeastward across Guadalupe, Caldwell, and Bastrop counties, its lateral extent is much smaller—about 100 miles—and cumulative displacement

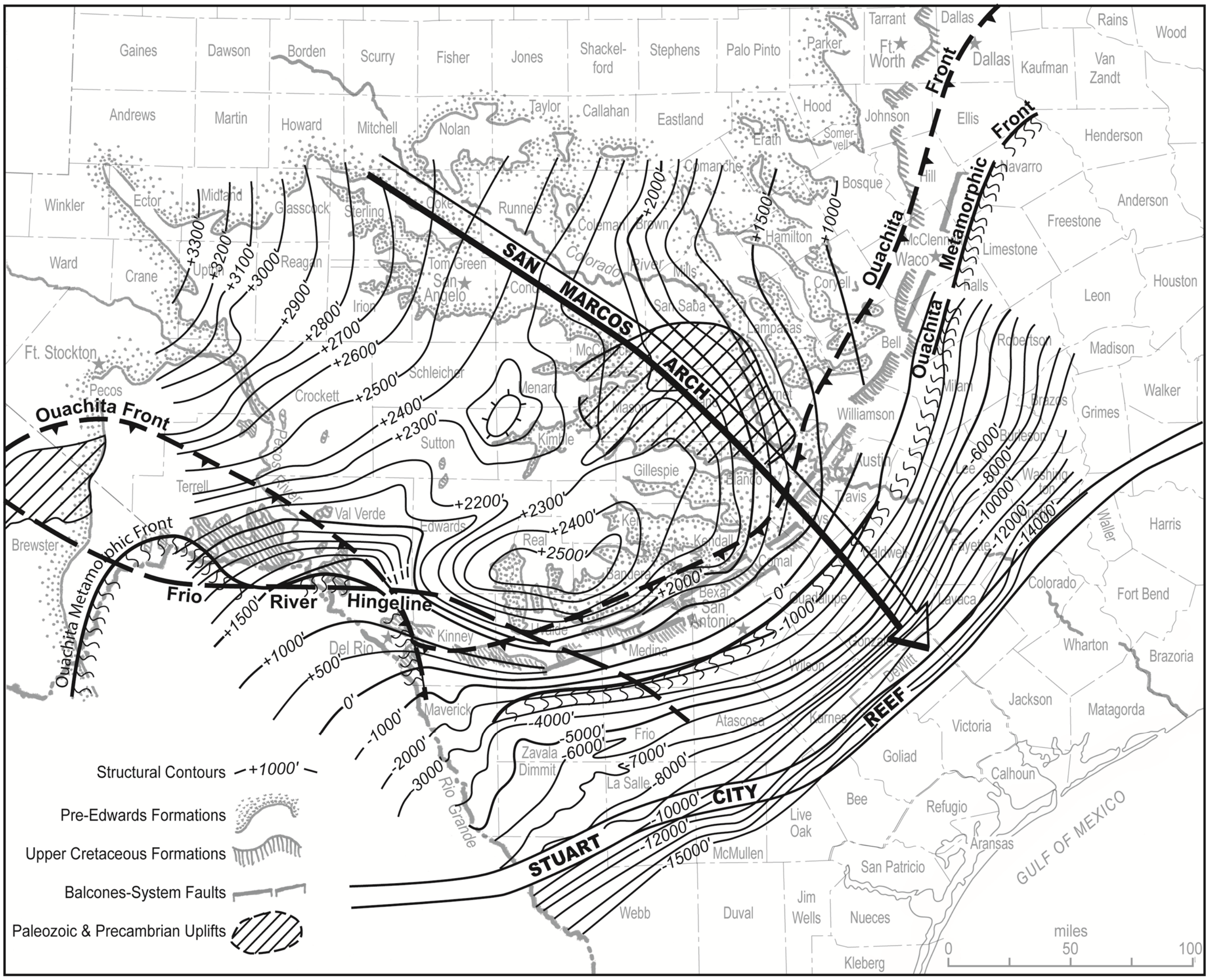


Figure 6. Structure (restored) on top Edwards and equivalents (Lower Cretaceous), Central Texas (from Rose, 1972, 1986a, 1986b, 2004).

somewhat less, perhaps 1200–1500 feet. Three lines of evidence suggest probable Oligocene or early Miocene movement of the Luling Fault Zone:

(1) its antithetic relationship with the Balcones Fault Zone, known to be late Oligocene to middle Miocene;
(2) where the main Luling Fault comes to the surface in the San Marcos River, it displaces Eocene formations, so it is at least as young as Eocene; and
(3) isopachous mapping of Upper Cretaceous through Eocene formations indicate no thickness variations responsive to fault movements—i.e., fault movement occurred post-Eocene.

However, there are two other dominant fault systems in the subsurface of South-Central Texas that were active during Edwards deposition (and afterward). Both lie downdip from and broadly parallel to the Balcones-Luling system:

The Mexia-Talco Fault Zone of the East Texas Basin, a narrow synthetic-antithetic graben, extends southward across Milam, Lee, Bastrop, and Gonzales counties, about 20 miles downdip of the Luling Fault Zone (Weeks, 1945b); and

The Karnes and Atascosa troughs (Rose, 1972) are similar antithetic-synthetic graben systems that stretch NE–SW across southeastern Gonzales, northwestern Karnes, and northern Atascosa counties.

Ewing (1991) correctly noted the coincidence of these narrow extensional features with the pinchout edge of the underlying Louann Salt (Jurassic), ascribing their origin to gulfward gliding, beginning late in the Late Jurassic and probably continuing even to the present day. Dramatic fault-related thickness variations are especially apparent in the Karnes Trough, beginning with the Kainer Formation (lower Edwards).

Balcones-Luling Late Cretaceous Volcanism

Ewing (1991) pointed out the presence of more than 200 volcanoes of ultramafic alkaline composition scattered along a trend located roughly midway between the Balcones Fault Zone and the antithetic Luling Fault Zone, and opposite the Balcones Fault Zone. These were mostly submarine volcanoes that erupted during Santonian and Campanian time. This episode of widespread, very deep-sourced volcanism, predating (Miocene) Balcones faulting by some 50 million years, may be significant as it relates to the origination of early regional uplift of the Edwards Plateau.

LOWER CRETACEOUS REGIONAL DEPOSITIONAL ELEMENTS AND HISTORY

During the early Cretaceous, mostly shallow marine and peritidal carbonate sediments accumulated on a vast, flat submarine plain called the Comanche Shelf (Rose, 1972). The Chihuahua Trough bordered the Comanche Shelf on the west, and merged northward with the tectonic trough along the eastern margin of the rising Rocky Mountains. Northward, the Comanche Shelf merged with the shelf on the east side of the Cretaceous Interior Seaway, in eastern Colorado, western Kansas, and northeastern New Mexico.

The Albian Gulf of Mexico Basin bordered the southeastern margins of the Comanche shelf (Fig. 7), marked by a long, narrow belt of skeletal carbonate sediments, the Stuart City Reef (Winter, 1961). Seaward of the Stuart City, water depth apparently increased steadily, so that open-marine pelagic carbonate sediments accumulated in oceanic water hundreds, even several thousands of feet deep. On the Comanche Shelf, however, water was generally quite shallow, although there were broad, structurally-controlled depressions and swells in the interior of the shelf that exerted great influence on thickness and lithology of the Edwards and its associated formations. The two dominant depressions were the Maverick Basin (Winter, 1961) on the southwest, and the East Texas Basin (North Texas–Tyler Basin of Fisher and Rodda, 1969) on the north and northeast. Separating these two depressions was a broad, elongate swell, the Central Texas Platform. The structural and depositional axis of the Central Texas Platform, the San Marcos Arch, was the dominant influence on facies and thickness of all Cretaceous formations in Central Texas. So the broad area of deposition between (1) the San Marcos Arch on the northeast; (2) the lee side of the Stuart City Reef to the southeast; and (3) the lee side of the Devils River Trend to the southwest constituted a vast offshore sediment trap where peritidal carbonate sediments could accumulate, mostly free of terrigenous sediment influence. All the carbonate rocks now included in the Edwards Group accumulated as two distinct depositional cycles of very shallow marine and peritidal sedimentary environments on the Central Texas Platform. To say that "an Albian geologist could have snorkeled, waded, or walked all the way from San Angelo to Gonzales" (more than 200 miles) would be no exaggeration.

For purposes of this summary, resorting to the commonly used Division concept of Hill (1887, 1901), resurrected by Lozo and Stricklin (1956) and Lozo (1959a, 1959b)[3], serves to simplify and facilitate discussion by dealing with two cycles as regional time-rock units. The lower cycle is wholly Fredericksburg (approximately middle Albian), whereas the upper cycle is all lower Washita (upper Albian). A third cycle, upper Washita, comprising the Del Rio and Buda formations, is entirely lower Cenomanian; it represents a final flooding of the Comanche Shelf at the end of the Comanchean Epoch (end of Washita as well as end of early Cenomanian).

Maverick Basin

The Maverick Basin originated as a NW–SE fault-bound rift valley in eastern Maverick County, filled with coarse terrigenous clastics of Triassic or lower Jurassic age (Scott, 2004). Such rift valleys are part of the Rio Grande Aulocogen (Walper, 1977), the structural precursor of the Rio Grande Embayment. Beginning in Aptian time, the Sligo shelf margin bridged the Rio Grande Embayment, adding a depositional aspect to the Maverick Basin. A closed elongated (E–W) thicker section of Pearsall Shale formed a few miles to the east, behind the Sligo shelf margin (Loucks, 1977). During Fredericksburg deposition the Stuart City Reef, by now having shifted a few miles north of its Sligo counterpart, also bridged the Rio Grande Embayment as a narrow E–W carbonate bank. A much larger "oval bowl" now developed behind the Stuart City bank, filled with euxinic carbonate mudstones and bedded anhydrite, the McKnight Formation (Lozo and Smith, 1964). During the early Washita, stratigraphic relief on clinoform surfaces sloping into the Maverick Basin suggest water depths of about 200 feet; however, the Maverick depression had become completely filled by the end of early Washita time, and ongoing subsidence during sedimentation was the probable cause of basin-filling during the following Del Rio, Buda, and Eagle Ford depositional episodes (Hentz and Ruppel, 2010). By the end of Austin deposition, however, the closed character of the Maverick Basin had been succeeded by a simple trough-configuration, opening southeastward toward the Gulf, reflecting more characteristically the configuration of the Rio Grande Embayment.

Devils River Trend

Rimming the Maverick Basin on the north was an arcuate, stratigraphically undivided Fredericksburg-Washita belt of patch reefs and thick beds of coarse-grain bioclastic sediments, the Devils River Trend (Lozo and Smith, 1964), best described as a more sheltered, lower wave-energy version of the Stuart City Reef. Miller (1984) demonstrated that local marker beds could be traced through the Devils River Bank into the Maverick Basin.

North Texas–Tyler Basin

On the northeastern flank of the San Marcos Arch, peritidal and very shallow-marine Edwards sediments (Person Formation) thin northeasterly and grade into slightly deeper marine shelf environments (Georgetown Formation) of the North Texas–Tyler Basin or East Texas Basin (Scott et al., 2003), which has a well-established basinal history through the Cretaceous and Tertiary. Gradual northeasterly Georgetown thickening from the San Marcos Arch and north-sloping clinoforms indicate water depths of several hundred feet. Lateral facies changes are also compatible with such basinward thickening.

[3]As explained by Smith et al. (2000, p. 6, after Lozo, 1959a), "the Cretaceous rocks of Texas are separated into two physically defined chronostratigraphic series – Comanchean (lower) and Gulfian (upper), thought to be long-term cycles of deposition. The Comanche-Gulf boundary is mid-Cenomanian in age. . . The Comanche Series is subdivided into three subcycles – Trinity, Fredericksburg, and Washita – each comprising a basal clastic-upper carbonate couplet recognizable across North, East, and Central Texas, and each referred to as a 'division'. Divisions are in concept identical to the provincial series and may also have "subdivisions". These couplets, regional in distribution, apparently resulted from, or were coupled with, episodic rejuvenation of terrigenous clastic source areas, with increased supply of clastics to the overall depositional basin, followed by carbonate deposition as clastic influx decreased; the boundaries may be unconformable or conformable." However, the precise stratigraphic location of the Fredericksburg-Washita boundary within the Edwards Group of the Central Texas Platform is not a regional disconformity (Smith et al., 2000; Rose, 1972, 2016). The pragmatic solution proposed by Smith et al. (2000) is adopted here: on the Central Texas Platform the hyphenated term Fredericksburg-Washita comprises all Edwards Group formations, and the approximate position of the equivalent boundary is projected to lie in the upper part of the Burt Ranch Member of the Segovia Formation in the Edwards Plateau, and at the base of the Regional Dense Member of the Person Formation along the Balcones Fault Zone and in the subsurface.

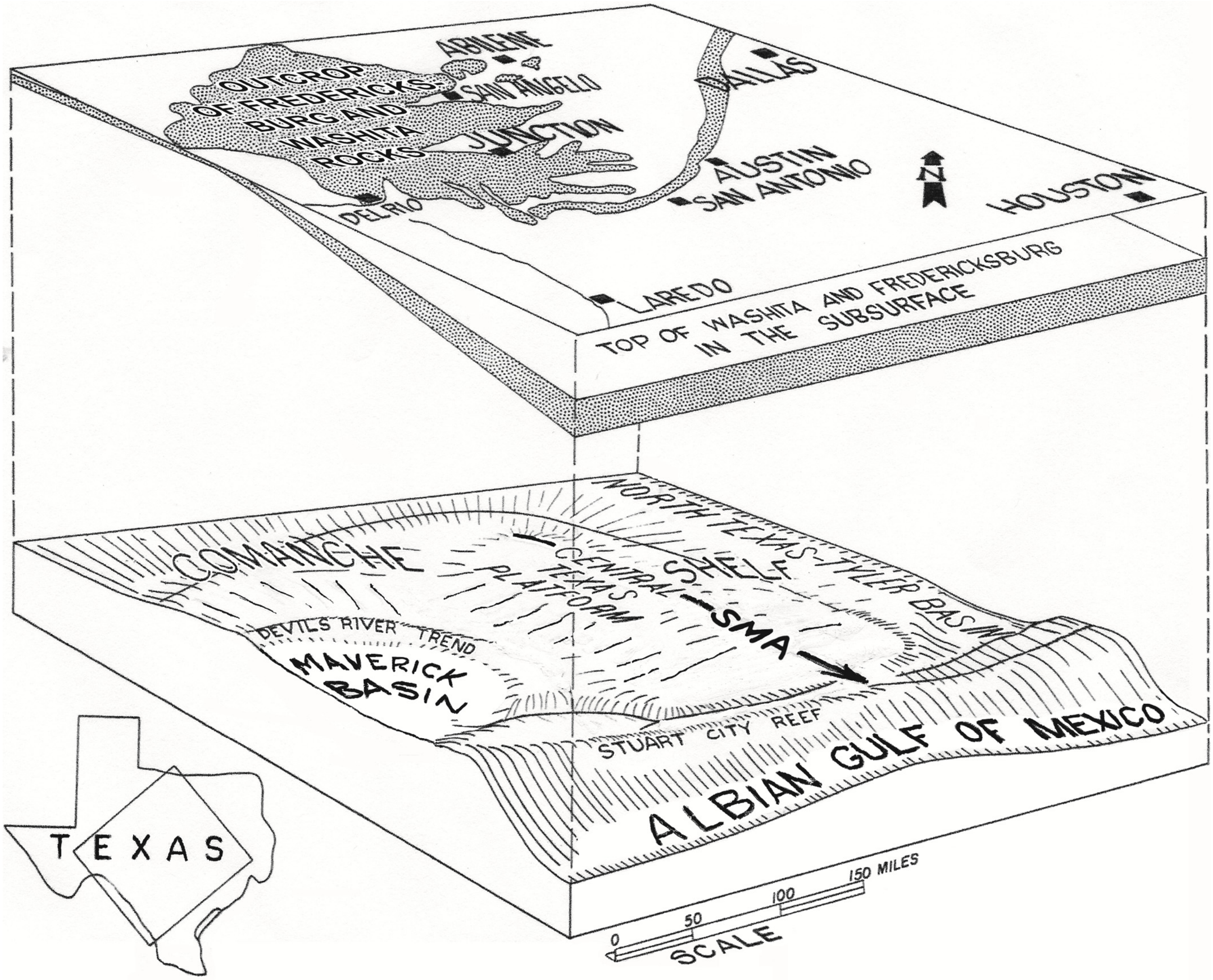


Figure 7. Regional depositional elements, Central Texas, end of Albian (modified after Rose, 1972).

DISTRIBUTION AND PALEOGEOGRAPHY OF THE EDWARDS GROUP, CENTRAL TEXAS

The Edwards Group, comprising a Fredericksburg and a lower Washita cycle, forms a wedge of shallow shelf carbonate strata that thickens southwestward from less than 400 feet on the crest of the San Marcos Arch to more than 1200 feet in the Maverick Basin (Fig 8). Southeastward, the Edwards thickens gulfward along the crest of the San Marcos Arch, from 400 feet at San Marcos, to more than 800 feet in the Karnes Trough, before grading into the back of the Stuart City Reef. Marine Edwards equivalents (Walnut, Comanche Peak, and Goodland formations) thicken northeastward to more than 900 feet in the East Texas Basin.

Figure 9 shows depositional environments of the lower Washita, the upper of the two Edwards cycles. Bathymetric relief off the seaward edge of the Stuart City Reef was in excess of 1000 feet, ranging deeper farther offshore. The Central Texas Platform constituted the restricted center of tidal and intertidal carbonate sedimentation, covering about 25,000 square miles. Paleotopographically, it effectively can be considered to represent upper Fredericksburg and lower Washita sea-level, based on the very shallow-shelf to tidal-flat depositional environments present. The San Marcos Arch was the linear crest of the Central Texas Platform, and the Llano Uplift was its culmination. Deposition on either side of the San Marcos Arch was markedly asymmetric: the apron of low-energy, shallow-marine shelf deposits was much narrower on the northeast flank of the arch than on the southwest flank.

Bathymetric relief—probably gradual rather than abrupt—into the East Texas Basin was roughly several hundreds of feet. Comparable bathymetry was also present—over a broad belt of decline—along the northwestern margins of the Central Texas Platform (Smith et al., 2000), where shallow-marine carbonate shelf strata of the Fort Lancaster Formation slope gradually into the Fort Stockton Basin, through pelagic open-shelf limestones into somewhat deeper pelagic open-shelf marls of the Boracho Formation, indicating bathymetric relief of 100 to 200 feet. Southwestward from the San Marcos Platform, the lower Washita-age cycle in the Maverick Basin was filled by fine, pelagic, Georgetown-age lime mudstone assigned to the Salmon Peak Formation.

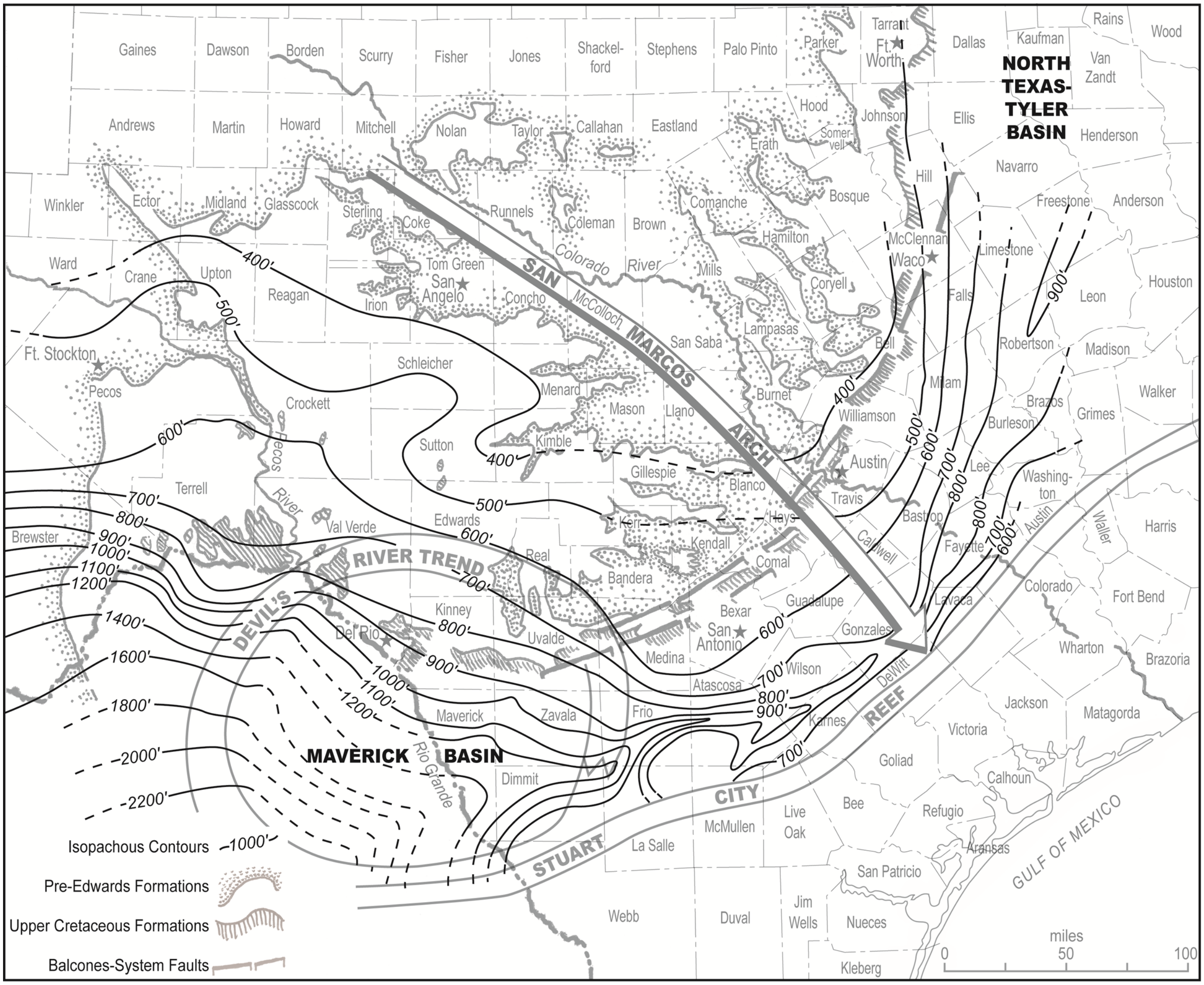


Figure 8. Isopach map of Edwards Group and associated formations (Washita-Fredericksburg Division) (after Rose, 1972, 1986a, 2004).

DISTRIBUTION OF DEL RIO AND BUDA FORMATIONS (LOWER CENOMANIAN)

The third cycle, comprising the lower Cenomanian Del Rio Clay and Buda Limestone, constitutes a terrigenous clastic-carbonate couplet that is much thinner and more uniform lithologically than the two underlying Edwards cycles which it succeeds.

The Del Rio expresses a temporary influx of smectitic clays and muds into an otherwise shallow-marine carbonate mud environment (a harbinger of things to come in the Late Cretaceous). The Del Rio is 20–40 feet thick over the San Marcos Arch, thickening northeastward to more than 100 feet in the East Texas Basin (Fig. 10). Southeastward from the Karnes Trough toward the Stuart City Reef, it pinches out between underlying Edwards rocks and the overlying Buda. It pinches out similarly along a west-bearing trend on the south flank of the Edwards Plateau, north of the Devils River Trend, and south of the San Marcos Arch, that extends westward into the Big Bend region. The Del Rio thickens to more than 300 feet in the Maverick Basin, probably as the result of compaction and subsidence during sedimentation.

The Buda Limestone is a thin, widely extensive, low-energy pelagic limestone that represents a final and complete flooding of the Comanche Shelf by shallow-marine seas. It is consistently 40–80 feet thick over the San Marcos Arch and into the East Texas Basin (Fig 11). It thickens gradually to as much as 160 feet in the Maverick Basin, and is 60–120 feet thick along the western reaches of the Frio River line, in Val Verde, Terrell, and Brewster counties. It is 30–40 feet thick in extensive erosional remnants on top of the Edwards Plateau, resting unconformably on the Edwards. According to Bailey et al. (1945), along the western flank of the East Texas Basin the Buda is absent by erosional pinchout beneath overlying Woodbine terrigenous clastics (Upper Cenomanian), the lowest sequence of the Gulfian Series. The Buda is also absent north of an E–W line along the middle fork of the Concho River; whether this is due to Cretaceous erosion or non-deposition, or to erosion during the present geomorphological cycle is not known.

Although the Buda Limestone is seen to thicken over depositional basins, and to thin over depositional highs, it rarely pinches out. Thus it can be seen to mute—but not obliterate—depositional topography developed in the lower Washita Edwards deposits which it covers. Because of its very widespread

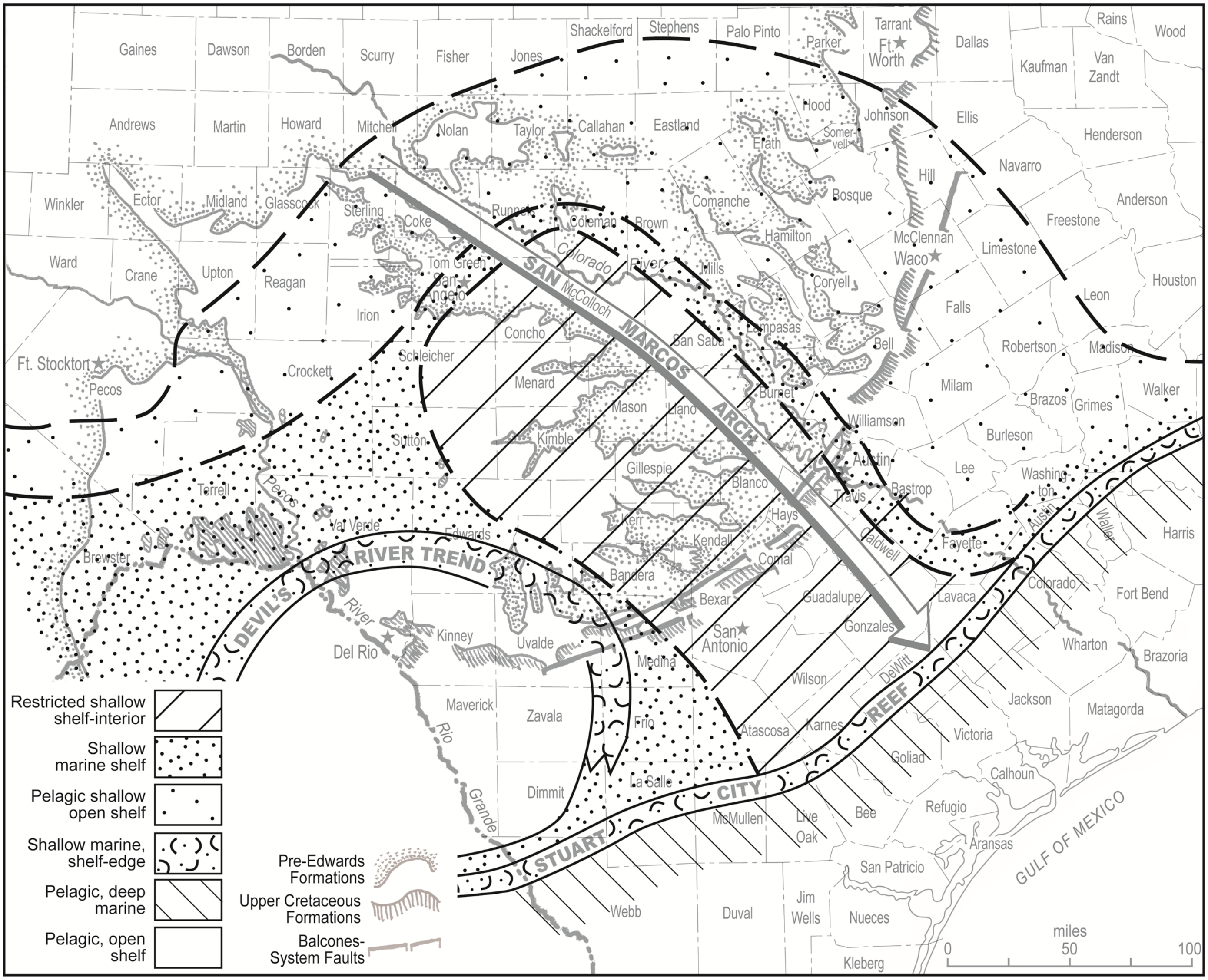


Figure 9. Regional depositional environments, upper Albian (after Rose, 1972; Smith et al., 2000).

and consistent nature, the Buda Limestone is a splendid, frequently used stratigraphic datum. It represents the final marine flooding of the Comanche Platform at the end of the Comanchean Epoch.

CENTRAL TEXAS AND THE CRETACEOUS WESTERN INTERIOR SEAWAY

Extensive and ongoing stratigraphic research among widespread and excellent outcrops has provided expanding knowledge and stratigraphic understanding of the immense epicontinental seaway that covered the western interior of North America during the Cretaceous Period. Kauffmann (1977) described the Western Interior Basin as structurally rather simple during the Cretaceous—a broad, elongated asymmetrical depression, with the western steep foredeep side adjoining the active Cretaceous Sevier Orogenic Belt, widespread subsidence in western structural troughs and the development of broad regional swells and localized basins that influenced sedimentation.

Kauffman describes three dominant marine pulses in the Cretaceous Western Interior Seaway of Colorado and Kansas (Fig. 12): (1) Kiowa–Skull Creek (= late Albian) cyclothem, (2) Graneros/Greenhorn (= middle and late Cenomanian) cyclothem, and (3) Niobrara (= Coniacian-Santonian) cyclothem.

In Texas, these cycles correspond roughly with (1) the Edwards Group and Georgetown Formation, and their lateral equivalents (Fredericksburg and lower Washita); (2) the Eagle Ford–Boquillas Formation, and (3) the Austin Chalk. Understanding the regional relationships between Cretaceous formations of Central Texas and those of the Cretaceous Western Interior Seaway—hundreds of miles to the northwest—provides a basis for extrapolating whether, where, and in what thickness, they may have extended west and northwest across the Comanche Shelf to connect with their equivalents in the southern end of the Western Interior Seaway.

Young (1986) indicated that the "fit" of the Texas Cretaceous cycles with those of the Western Interior Seaway is less than perfect, although an extended Albian inundation did occur in both areas, containing at least three flooding episodes. Two short-lived Cenomanian cycles follow the Albian transgression in Texas: Del Rio/Buda (middle Cenomanian), and Eagle Ford–Boquillas (late Cenomanian). According to Young (1986), no Turonian-age Eagle Ford–Boquillas is present on the San Marcos Arch/Central Texas Platform, whereas the Turonian is well repre-

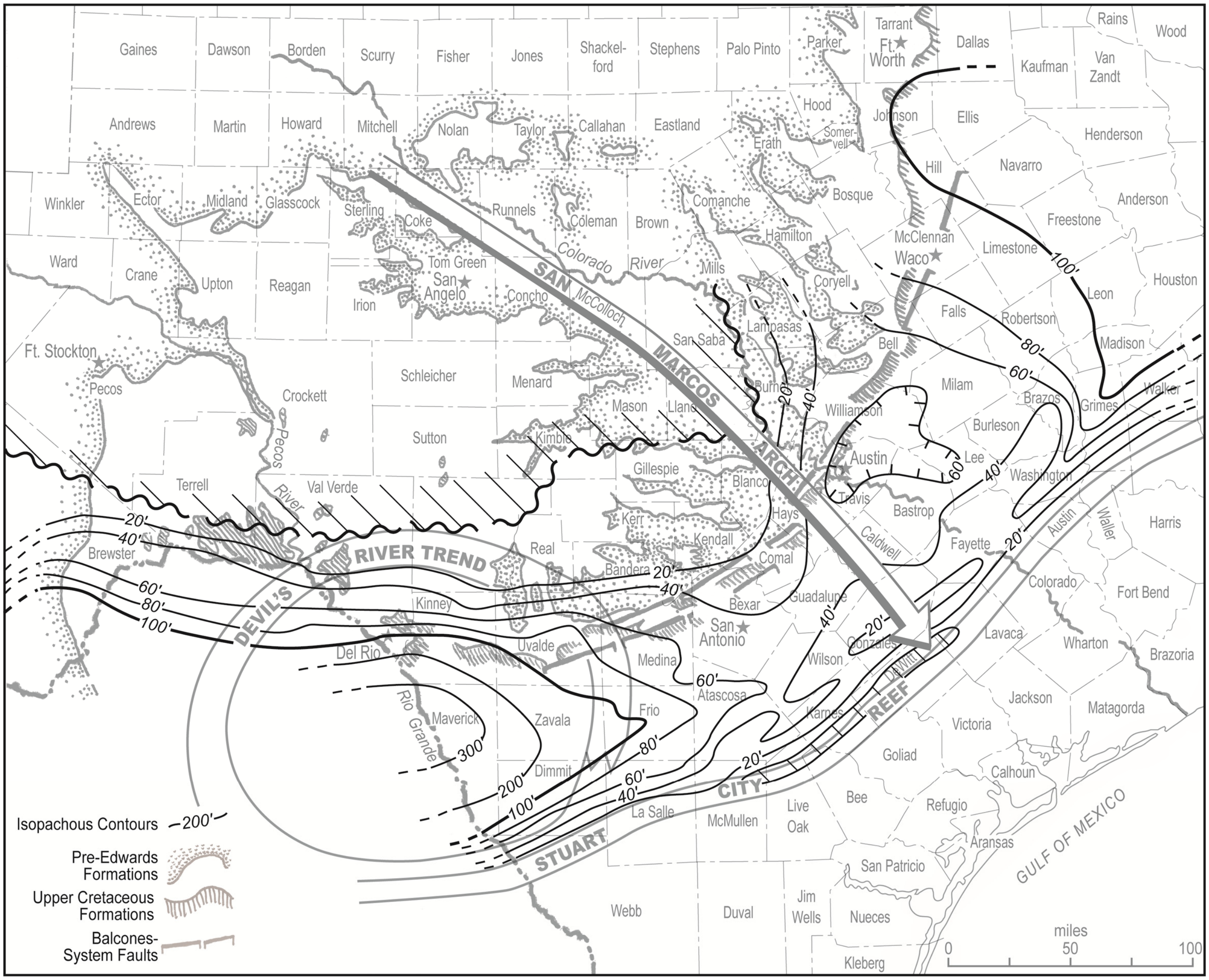


Figure 10. Isopach map of the Del Rio Clay (from Maxwell et al., 1967; Rose, 1972, 1986b; Smith et al., 2000).

sented in the Western Interior. Of course, the Turonian is present in the East Texas Basin and possibly also in the Rio Grande embayment (Hentz and Ruppel, 2010). On the San Marcos Platform, the Dessau Member of the Austin Chalk is lower Campanian, whereas the Niobrara Chalk of the Western Interior is older (Coniacian-Santonian). Young suggests that the imperfect match of these three dominant inundations reflects differing tectonic influences of the Western Interior before and during the Laramide Orogeny, versus the early subsidence of the ancestral Gulf of Mexico Basin.

It has long been known that the thick Albian carbonate successions of Texas and northern Mexico were represented in the Western Interior Seaway by terrigenous clastics assigned to the Plainview/Skull Creek/Kiowa and Muddy formations. Recent work by Lawton et al. (2004), Oboh-Ikuenobe et al. (2008), Lucas et al. (2010), and Scott et al. (2013) has established that the two provinces were separated by a low arch related to the older Las Animas Arch (Fig. 13).

However, the lithologic similarities of the Eagle Ford and Graneros/Greenhorn formations suggest that by late Cenomanian, the Texas area and the Western Interior Seaway had joined. The similarity of the Niobrara and Austin reinforce that interpretation. The obvious marine connection is through the Chihuahua Trough to the foreland trough in front of the Sevier Orogenic Front. But broad shallow shelves on the eastern side of the Western Interior Seaway, and the presumed merged northern flank of the Central Texas Platform with the western flank of the East Texas Basin, suggest another connection as well.

This raises questions as to how far to the northwest Eagle Ford and Austin strata may have extended in Texas, overlying the Central Texas Platform and westward from the East Texas Basin. However, the pinchout of the Eagle Ford–Boquillas onto the southwest flank of the San Marcos Arch on the Edwards Plateau suggests that the Western Interior Seaway may have been narrower to the south than it was in the Colorado-Kansas sector during the Cenomanian. Alternatively, the gentle bathymetric high of the earlier Edwards bank may have separated the deeper Chihuahua Trough on the west from the shallow-shelf setting of the western side of the East Texas Basin on the east.

Subsequent Upper Cretaceous formations in both Texas and the U.S. Western Interior represent progressive shallowing of Late Cretaceous seas, and increasingly terrigenous sedimentation.

DISTRIBUTION OF UPPER CRETACEOUS FORMATIONS, CENTRAL TEXAS

This section reviews distribution and thickness patterns of the Eagle Ford–Boquillas Formation, Austin Chalk, and the com-

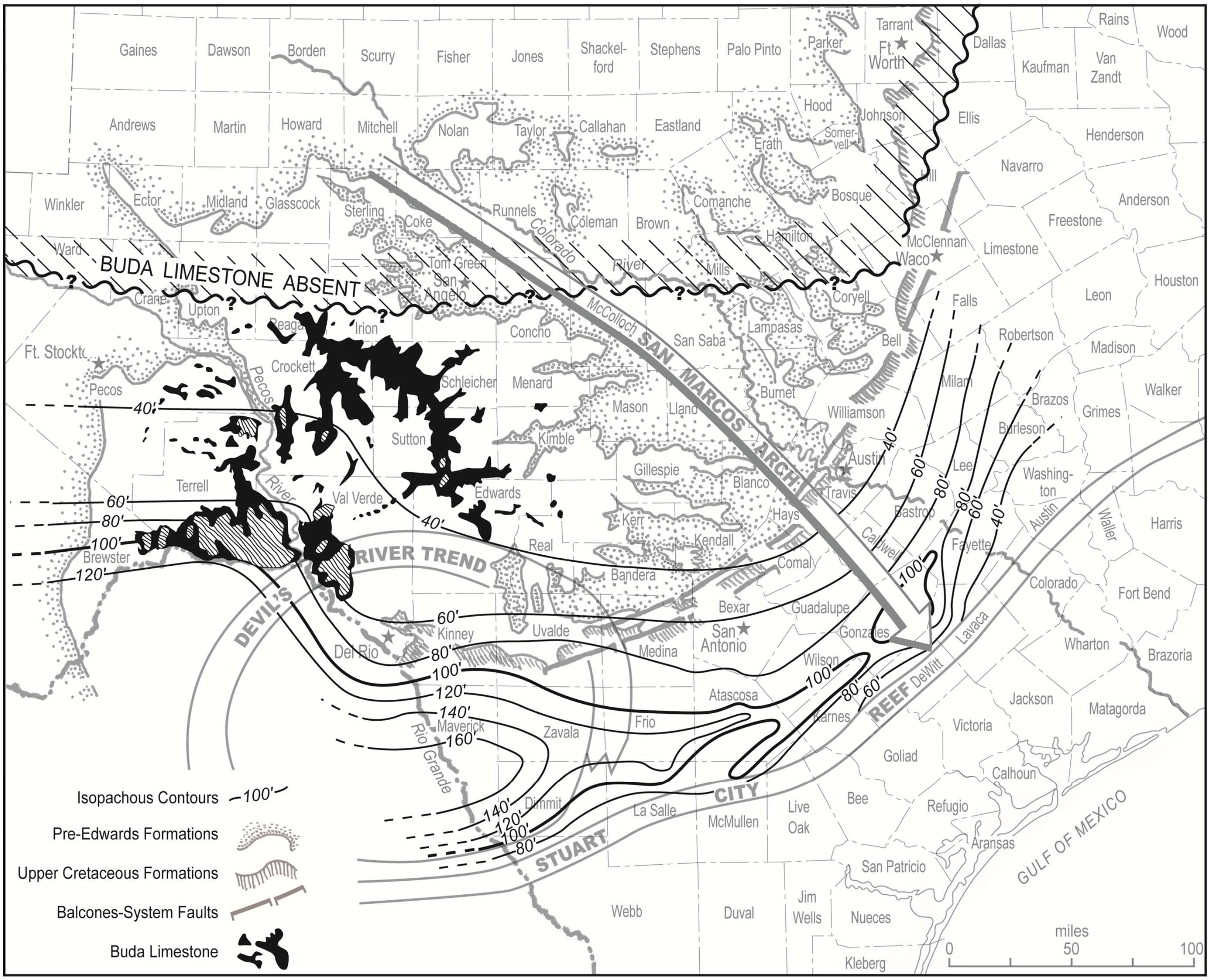


Figure 11. Isopach map of the Buda Limestone, with remnant outcrops on Edwards Plateau (from Maxwell et al., 1967; Rose, 1972, 1986a, 1986b; Smith et al., 2000; Texas Bureau of Economic Geology, Geologic Atlas of Texas (Del Rio [1977], Fort Stockton [1982], Llano [1981], Pecos [1975], San Angelo [1976], San Antonio [1983], and Sonora [1981] sheets).

bined Taylor and Navarro groups, all Upper Cretaceous, with a view towards projecting their possible presence and thickness in the area of the present Edwards Plateau.

Projected Thinning Diagrams

Projected thinning diagrams help predict how far shelfward formations may have extended before pinching out, based on isopachous contour mapping. In the present study, positioning the trend of all such diagrams along the crest of the stable, regional San Marcos Arch helps minimize the effects of regional or local subsidence. Shelfward thinning of time-stratigraphic formations typically assumes a regular profile that approaches an asymptotic form. Shelfward projection provides a realistic guide as to where original pinchout edges may have been located, before later erosion. Three counterpart thinning diagrams (Figs. 14, 18, and 21) project regular thinning patterns of Upper Cretaceous, Paleocene-Eocene, and Oligocene-Miocene formations from the Gulf Basin northwestward along the San Marcos Arch, across the Balcones/Ouachita Downwarp, the Balcones Fault Zone, the Llano Dome, and the Edwards Plateau.

Eagle Ford–Boquillas (Lower Cenomanian)

The Eagle Ford projected thinning diagram (Fig. 14) indicates that the Eagle Ford–Boquillas Formation was less than 20 feet thick across the Llano Dome, but thickened southeasterly across the Central Texas Platform toward the Stuart City Reef, from about 50 feet in the shallow subsurface over the San Marcos Arch to more than 300 feet in the Karnes Trough, before thinning over the crest of the Stuart City Reef. Regional thickness patterns are shown by Figure 15: at the outcrop in Austin, the Eagle Ford is between 25 and 30 feet thick. Over a few divide areas of the central and southwestern sectors of the Edwards Plateau, on the southwestern flank of the San Marcos Arch, very thin (<30 feet) outliers of Boquillas Formation (late Cenomanian, equivalent to the Eagle Ford Formation of central and south Texas) are present in broad erosional-remnant areas of Buda outcrop. Here the Boquillas consists of deeply weathered, calichified, platy flagstones of clayey and silty limestone, resting unconformably on the Buda Limestone. In southwest Texas, along the Frio River Hingeline, the Boquillas Formation is 100-200 feet thick (Donovan et al., 2012). The Eagle Ford occupies a closed (500-foot contour) depocenter in the Maverick Basin. To the south-

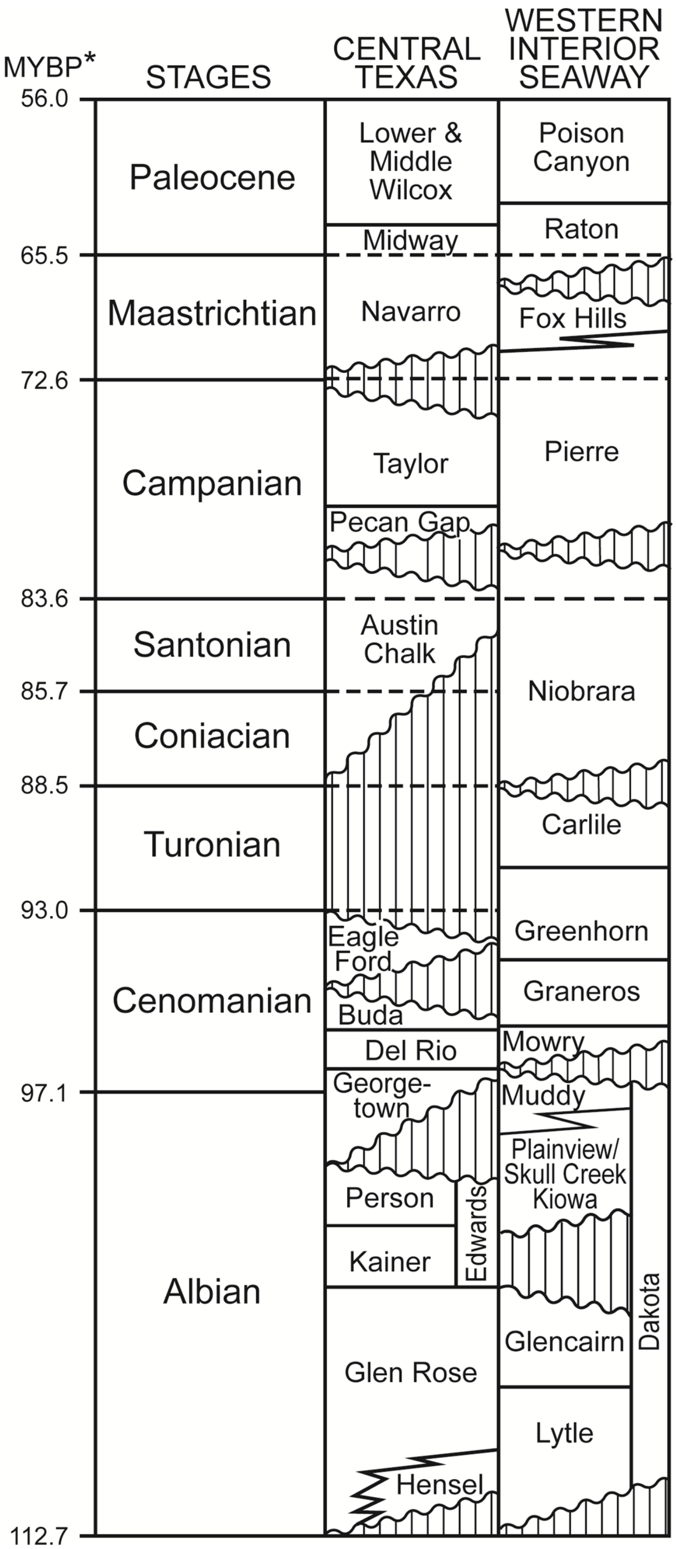


Figure 12. Correlation of Cretaceous successions, Central Texas and Western Interior Seaway (from Rose, 1972; Cook and Bally, 1975; Kauffmann, 1977; Young, 1986; Moore, 1996; Smith et al., 2000; Scott et al., 2003).

west, the Eagle Ford–Boquillas thickens into the Chihuahua Trough. Maxwell et al. (1967) report that in Big Bend National Park, the Ernst member (the part of the Boquillas that is equivalent to the Eagle Ford of central and north Texas) thickens southward from 277 feet at the north end of the park to 450 feet at Terlingua, to 1,000 feet at the village of Boquillas, in the southwest end. West of the map area, near Kent in northern Jeff Davis County, the Chispa Summit Formation or its near-equivalent, the Ojinaga Formation (Boquillas and Eagle Ford equivalent) is reported to be about 2,200 feet thick, thickening to the southwest. However, the upper part of that sequence is Coniacian, Santonian, and lowermost Campanian (Metz, 2000). A reasonable guess for the upper Cenomanian and Turonian parts of this interval—equivalent to the Boquillas—is about 600 feet thick.

The presence of erosional remnants of Boquillas Formation on the central part of the Edwards Plateau indicates that the plateau area was covered by Kaufmann's Greenhorn Cyclothem of the Western Interior Seaway. Whether the two areas were connected through the Chihuahua Trough and the foredeep of the Western Interior Seaway, or via the wide shallow shelf areas that lay to the east is not known.

Austin Chalk (Coniacian–Santonian–Lower Campanian)

The Austin Chalk is the counterpart (though not the direct contemporary) of the uppermost of the three great marine pulses of the Western Interior Seaway, correlating with the Niobrara Chalk. It represents pelagic deposition in quiet, clear-water marine-shelf settings largely free from influx of clay and silt, in water depths of 300–600 feet (Kaufmann, 1977).

Along the San Marcos Arch, the Austin Chalk thins northwestward from 500 feet or more near the Stuart City Reef to about 350 feet along the Balcones Fault Zone between Austin and San Antonio, indicating the beginnings of gulfward subsidence (Fig. 14). These thickness patterns suggest that the Austin may have been only about 200 feet thick over the most positive parts of the San Marcos Arch (the buried Llano Dome, and northwestward). Young (1986) postulated that only thin equivalents of the maximum transgressive unit, equivalent to the Dessau Chalk, would have reached to the northwesternmost extent of the San Marcos Arch, indicating thicknesses of less than 200 feet.

The Austin Chalk is not present in outcrops on the Edwards Plateau, except for its far southwestern margins, along the Frio River Hingeline, in the same area where the underlying Boquillas is present (Fig. 16). Erosional truncation at the top precludes determination of its true depositional thickness. This area represents the northern flank of the Chihuahua trough. Farther west, the Austin is present as the upper Boquillas and Pen formations of the Big Bend National Park area (Maxwell et al., 1967), where it thickens southward (like the Eagle Ford-equivalent Ernst Member), from about 350 feet in the northern sectors of the Park to more than 1,000 feet near Terlingua, and presumably even thicker on southward into the Chihuahua trough.

Three lines of evidence suggest that a thin Austin Chalk stratum did extend across the present Edwards Plateau, and connected with analogous Niobrara strata on the broad eastern shelf of the Western Interior Seaway:

(1) the presence of underlying Eagle Ford–Boquillas strata high on the southwest flank of the Edwards Plateau, correlative with the Greenhorn of the eastern shelf of the Western Interior Seaway, and their general lithologic similarity;
(2) the lithologic similarity between marine Austin Chalk and marine Niobrara chalk, and their known widespread regional distributions; and
(3) the presence of truncated Austin Chalk outcrops on the northwest flank of the Chihuahua Trough in the southwestern Edwards Plateau and Big Bend regions.

Taylor and Navarro Groups (Upper Campanian–Maastrichtian)

Based on Kaufmann's (1977) sea-level fluctuation charts, the Campanian and Maastrichtian represent a substantial and

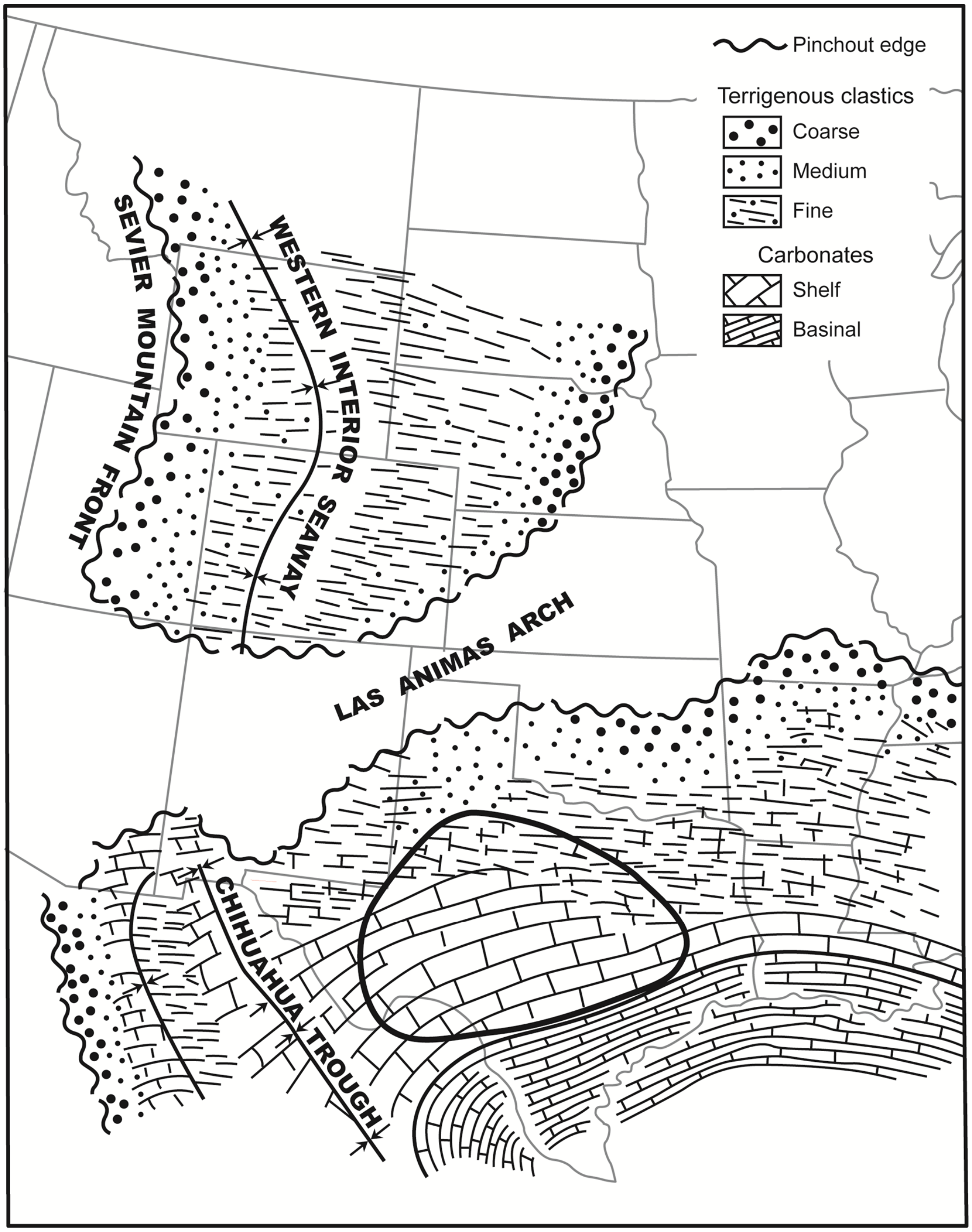


Figure 13. Generalized paleogeography, Cretaceous Western Interior Seaway, Wyoming to Texas (from Rose, 1972; Cook and Bally, 1975; Kauffmann, 1977; Scott et al., 2013).

increasing regression from the preceding Coniacian-Santonian marine transgression, so that the Western Interior Seaway was drained by the end of the Maastrichtian. Young (1986) generally agrees, except that he identified the Pecan Gap marl (middle Campanian) and Corsicana marl (middle Maastrichtian), as "last-gasp" invasions in an otherwise overall regressive cycle.

The Taylor and Navarro groups are combined herein for pragmatic mapping reasons—in the upper Gulf Coastal Plain, they tend to be similar lithologically, mostly calcareous marine mudstone, becoming increasingly sandy and silty upward in the Navarro part of the sequence, thus representing a gradual regional regression through the upper half of the Upper Cretaceous succession (Cook and Bally, 1975). Chalky and marly marine intervals are also present, as the Pecan Gap and Corsicana formations, and marine sandstones do intervene, however, as the Wolfe City (lower Taylor) and Nacatoch formations (upper Taylor).

Southeasterly along the axis of the San Marcos Arch (Fig. 14), the Taylor-Navarro apparently thickened from perhaps 400 feet northwest of the Llano Uplift to 1000 feet across the Balcones Fault Zone, to 2000 feet over the Stuart City Reef, to a maximum of 3500 feet reported by Cook and Bally (1975) midway between the Stuart City Reef and the present coast line. Based on projected thinning patterns, especially in the Gulf Coast, the stratigrapher should anticipate the rate of updip thinning to diminish asymptotally, so one would expect that the Taylor-Navarro sequence might be about 800 feet thick over the eastern part of the Llano Dome, thinning gradually northwesterly to a thickness of about 400 feet at the far northwestern margins of the present Edwards Plateau. In any case, however, only the more marine calcareous clay and marl units would be expected to penetrate farther onto the Central Texas Platform, as postulated by Young (1986).

Westward from the San Marcos Platform area, the Taylor-Navarro sequence shows (Fig. 17) clear evidence of gradual regional shoaling, with shallow marine carbonate buildups (Anacacho Formation), overlain by three separate regressive sand series, in upward order:

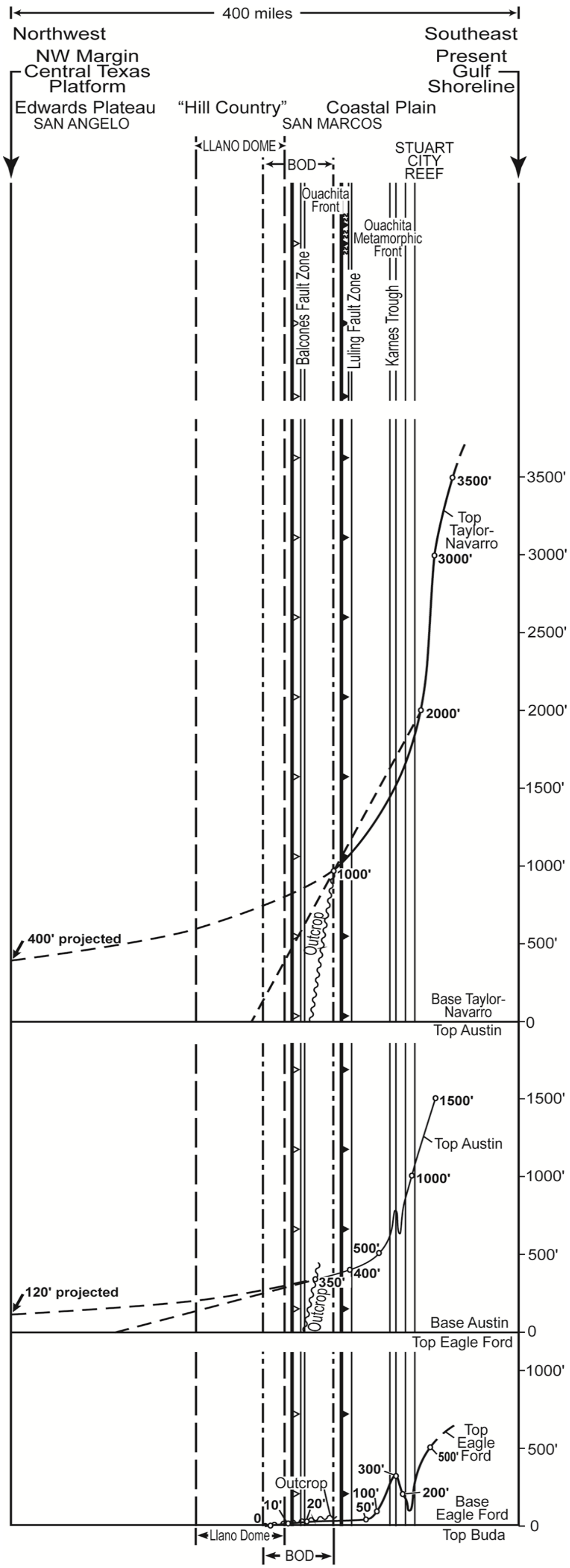


Figure 14. Projected northwest thinning of Upper Cretaceous formations along the San Marcos Arch, from Gulf Coastal Plain across Central Texas Platform.

(1) San Miguel, "characterized by relatively isolated wave-dominated deltaic sand bodies or shelf bars with no alluvial plains preserved" (Weise, 1980; Lewis, 1977, both cited by Ewing, 2003), and assigned to the lower Taylor Group (it is possible that the San Miguel is a lateral equivalent of the Anacacho Formation);
(2) Olmos, "characterized by a major delta system with attached coal deposits, strand-plains, and alluvial plains" (Tyler and Ambrose, 1986, cited by Ewing, 2003) and assigned to the upper Taylor or lower Navarro Group; and
(3) Escondido, middle to upper Navarro, which constitutes the uppermost of the three progradational depositional terrigenous clastic complexes.

Weise (1980) showed shallow marine San Miguel sand bodies in Maverick and Frio counties, and Ewing (2003) showed an Olmos coastal swamp (coal basin) in northwestern Maverick County (coincident with the present axis of the Rio Grande), with two delta systems adjacent to the southeast and east. Working farther downdip in Webb County, Snedden and Kersey (1982) identified one of the Olmos delta systems, as well as a deeper-water marine sand facies.

Taylor-Navarro strata are missing over the Marathon Dome of Terrell and Brewster counties, and also across the Rio Grande in the Serrania del Burro Uplift, indicating Laramide uplift in both areas. Farther west, in the Big Bend National Park, the Taylor and Navarro groups are represented by the Pen-Aguja-Javelina sequence, a southward-thickening regressive succession starting with marine mudstone at the base and culminating in continental terrigenous clastics. Thickness of this succession ranges from about 1200 feet at the north end of the park to more than 2500 feet to the south (Maxwell et al., 1967), expressing southward and westward thickening into the Chihuahua Trough.

From the south, it may be speculated that the Taylor-Navarro succession would have been perhaps 500 feet thick over the shelf-break along the front of the Devils River Bank, with continued gradual northward thinning toward the axis of the San Marcos Arch (Fig. 17). However, this estimate must be tempered by the recognition that, regionally, the Taylor-Navarro succession in the Rio Grande Embayment is clearly regressive, with shallow-marine shelf carbonates, succeeded upward by the three clastic regressions (San Miguel, Olmos, and Escondido), each of which included sea-level or even coastal plain deposits. Given the very low topographic relief that must have existed along the margins of the Central Texas Platform, and the composition of the three Taylor-Navarro clastic sand series, it seems unlikely that substantial thicknesses could have been deposited over the Plateau during Taylor-Navarro time, except for full-marine clays or marls such as the Upson, Pecan Gap, or Corsicana equivalents. Indeed, Ewing (2005) suggested that "[t]he Llano area was probably land and perhaps a sediment source during some of the later part of the Late Cretaceous." Deltaic sediments were deposited southwards into the arc southwest of San Antonio during the San Miguel and Olmos progradations (Ewing, 2003b), and clastic input to the east has also been inferred for the Wolfe City sandstone between Austin and Waco. The Llano area may have formed a southern sill or constriction to the Western Interior Seaway, with limited faunal and seawater exchange between it and the Gulf of Mexico. According to Young (1986), "[t]he only time in the late Campanian and the Maastrichtian during which the San Marcos Arch was likely to have been inundated was in the middle Maastrichtian. [The] Corsicana Formation . . . per-

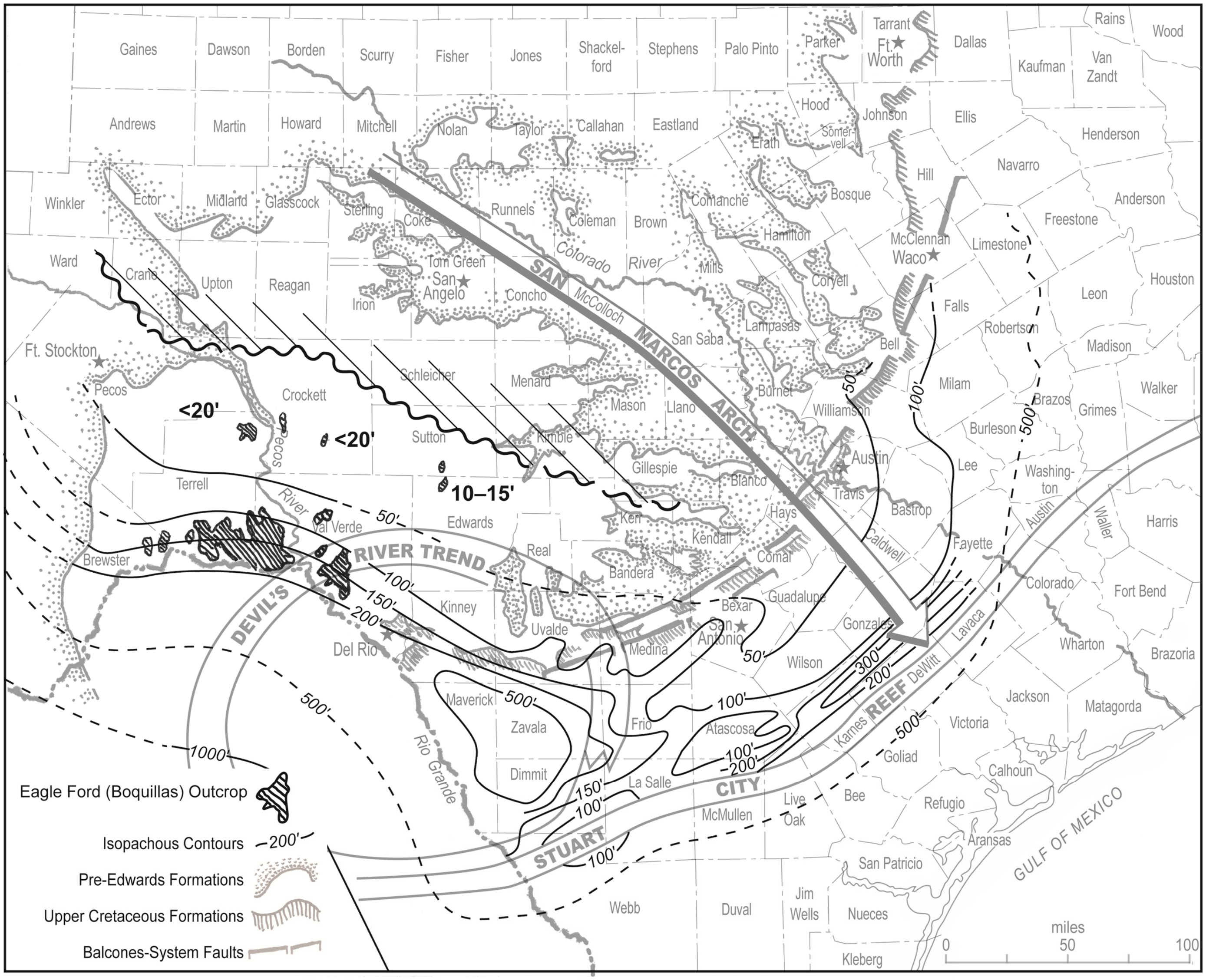


Figure 15. Isopach map of Eagle Ford–Boquillas Formation (from Maxwell et al, 1967; Rose, 1972; Cook and Bally, 1975; Texas Bureau of Economic Geology, Geologic Atlas of Texas (Del Rio [1977], Emory Peak–Presidio [1979], Fort Stockton [1982], Llano [1981], Pecos [1975], San Angelo [1976], San Antonio [1983], and Sonora [1981] sheets).

haps much thinner than in the East Texas Basin, or even on the outcrop along its southwest flank, probably did extend across the San Marcos Platform."

Farther west, southward thickening of the regressive Taylor-Navarro sequence in the Big Bend region (especially with substantial continental deposits toward the top) would seem to suggest that it might have thinned to about 500 feet in Terrell or southern Crockett County.

Honoring all facts and pertinent structural and stratigraphic patterns, it is suggested that only about 500 feet of Taylor-Navarro marine calcareous muds and marls extended onto what is now the apex of the Edwards Plateau. They would have been thickest on the southern flanks, and continued to thin northward toward the San Marcos Arch and the Llano Dome. Presumably they extended even farther northerly, beyond the San Marcos Arch, into the now-eroded western reaches of the East Texas Basin.

In any case, it is probable that, beginning in late Campanian time, weathering and meteoric ground water processes began to act, during intermittent periods of subaerial exposure, on the thin mantle of Upper Cretaceous sediments covering the western part of the Central Texas Platform, as well as the Lower Cretaceous carbonates below them.

DISTRIBUTION OF CENOZOIC FORMATIONS, EDWARDS PLATEAU REGION AND ADJACENT

Based on facts and interpretations presented thus far, the vast Edwards carbonate bank of the Central Texas Platform, at the end of Cretaceous time, was a low-lying island or shoal covered by 600 to 1000 feet of Upper Cretaceous chalks and marls. The San Marcos Arch was the crest of that low massif, and the highest parts along the axial crest overlay the Llano Dome and northwest. Relict topography, inherited from that Edwards bank, sloped gently outward from its periphery. During the Paleocene and Eocene, such lower marginal areas would have received sediments first, before the old crest was finally covered.

This section is based mostly on isopach maps from Cook and Bally (1975) as well as lithofacies maps and discussions of Galloway et al. (2011).

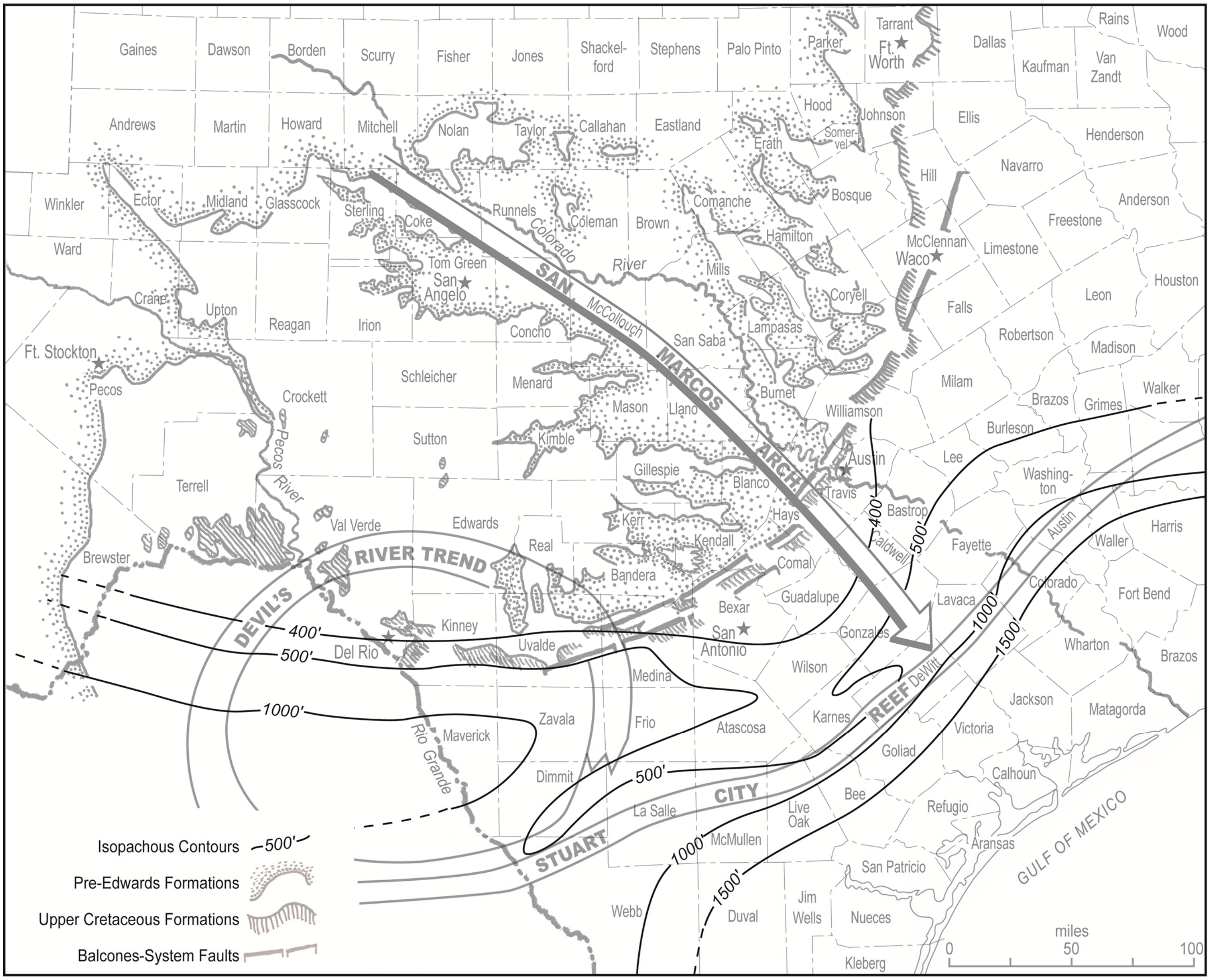


Figure 16. Isopach map of Austin Chalk and equivalents (from Maxwell et al., 1967; Cook and Bally, 1975; Texas Bureau of Economic Geology, Geologic Atlas of Texas (Del Rio [1977], Emory Peak–Presidio [1979], Fort Stockton [1982], Pecos [1975], San Angelo [1976], San Antonio [1983], and Sonora [1981] sheets).

Midway and Lower and Middle Wilcox Group (Lower and Upper Paleocene)

The Paleocene Series in the Texas Gulf Coast consists of a thin transgressive marine mudstone below and a much thicker regressive clastic series above, the lower and middle parts of the Wilcox Group as shown in Figure 18, illustrating northwestward thinning of the Paleocene and Eocene formations along the San Marcos Arch, from the Gulf Coast Basin across the Llano Dome and beyond, into the western Edwards Plateau. The entire Paleocene ranges in thickness between zero along the inferred pinchout edge over the Balcones/Ouachita Downwarp, Llano Uplift and southern Edwards Plateau, and 2000 feet in the Rio Grande Embayment of south Texas (Fig. 19).

Midway Formation

The Midway Formation is a consistently thin (100–300 feet) transgressive marine mudrock, representing sediment starvation, and the most west-reaching flooding surface among all the Cenozoic formations of the Gulf Coast. Galloway et al. (2011) projected the updip pinchout edge of the Midway to lie a few miles north of the Devils River Bank, curving eastward around the northeastern flank of the Llano Uplift, then trending northward along the old Bend Arch. They show the maximum progradational shoreline of the Midway as trending northward across the buried Maverick Basin, crossing the Balcones Fault Zone near Uvalde, then forming a convex arc above the Balcones/Ouachita Downwarp, around the San Marcos Arch inboard (west and north) from the present Balcones Fault Zone by a distance of 20–50 miles, and trending thence northward along the Balcones/Ouachita Downwarp, toward Fort Worth (Fig. 19). Presumably, thin coeval marine and coastal plain sediments lay west of the maximum progradational shoreline, and may well have covered the Llano Dome, even reaching to the far northwestern margins of the present Edwards Plateau. Midway-age sediments were almost certainly thinner over the buried crest of the San Marcos Arch than on the flanks of the Central Texas Platform. Estimated Midway thickness is about 200 feet over the Balcones Fault Zone, and perhaps 100 feet over the west side of the Llano Dome.

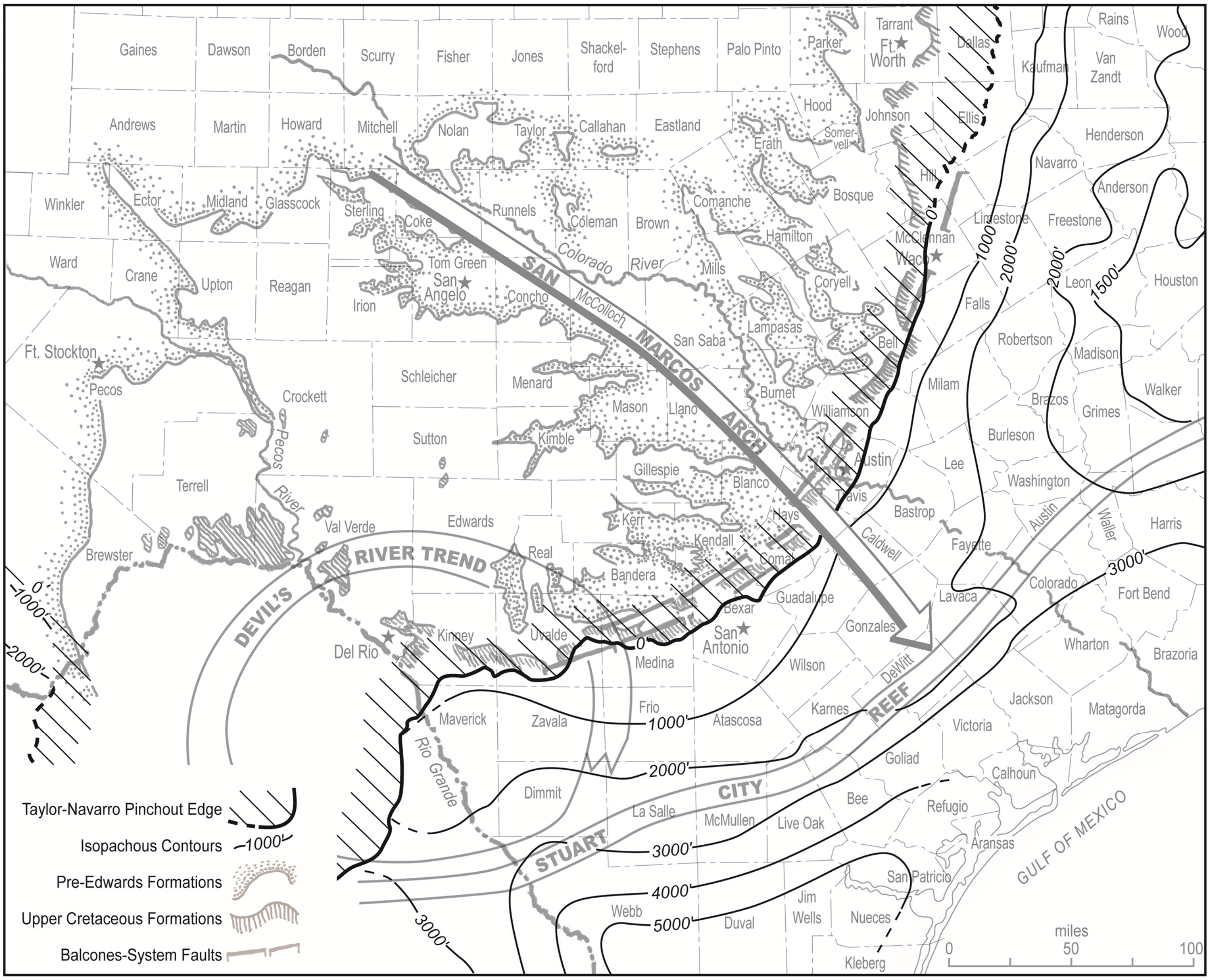


Figure 17. Isopach map of Taylor and Navarro groups (from Maxwell, 1967; Cook and Bally, 1975; Texas Bureau of Economic Geology, Geologic Atlas of Texas (Del Rio [1977], Emory Peak–Presidio [1979], Fort Stockton [1982], Pecos [1975], San Angelo [1976], San Antonio [1983], and Sonora [1981] sheets).

Lower and Middle Wilcox Formation

The upper Paleocene is represented by the lower and middle parts of the Wilcox Formation, a regressive terrigenous clastic succession perhaps 300 feet thick over the Balcones Fault Zone, thickening downdip to more than 1500 feet beyond the Stuart City Reef (Fig. 19). North of the San Marcos Arch, Galloway et al. (2011) show the original western edge of the late Paleocene (= lower and middle Wilcox) coastal plain to roughly follow the western (inboard) edge of the Balcones/Ouachita Downwarp. The inboard edge of the late Paleocene coastal plain arcs southwestward around the San Marcos Arch, bears west-southwest across the southern flank of the Edwards Plateau, then curves to the southwest, crossing the Devils River fairway into the Maverick Basin before trending into Mexico, south-southeast (parallel) to the Rio Grande, and pinching out on the northeastern flank of the Burro-Peyotes Arch. By late Paleocene, the maximum regressive shoreline had receded far coastward from its early Paleocene position—about 50 miles in the Rio Grande Embayment, nearly 100 miles in the San Marcos Arch sector, and about 200 miles in the East Texas Basin.

Given that late Paleocene alluvial, deltaic, and coastal plain sediments were being deposited on the flanks of the low-lying Central Texas Platform, its crest (the San Marcos Arch) must have been subaerially exposed. Covered by a thin mantle of lower Paleocene soft mud and sand above soft Taylor-Navarro marl and mudrock, the axis of the San Marcos Arch must have been a broad, low-relief topographic feature; it is difficult to envision much erosion or sediment transport from that source onto the depositional early and middle Wilcox coastal plains. Most of the alluvial-plain sediments would probably have been derived from the ancestral Rio Grande and from the Burro-Peyotes highlands to the west, and the ancestral Colorado River to the east (Galloway et al., 2011), and distributed by coastal rivers and longshore drift. Finally, we must assume that weathering and meteoric ground-water processes were acting on the mantle of Upper Cretaceous and lower Paleocene formations as well as the Lower Cretaceous carbonates below.

In any case it is unlikely that more than a thin (200 feet?) updip veneer of late Paleocene coastal plain sediments or weathered soils may have covered the southeastern flank of the Edwards Plateau, in what is now Edwards, Real, Kerr, Gillespie,

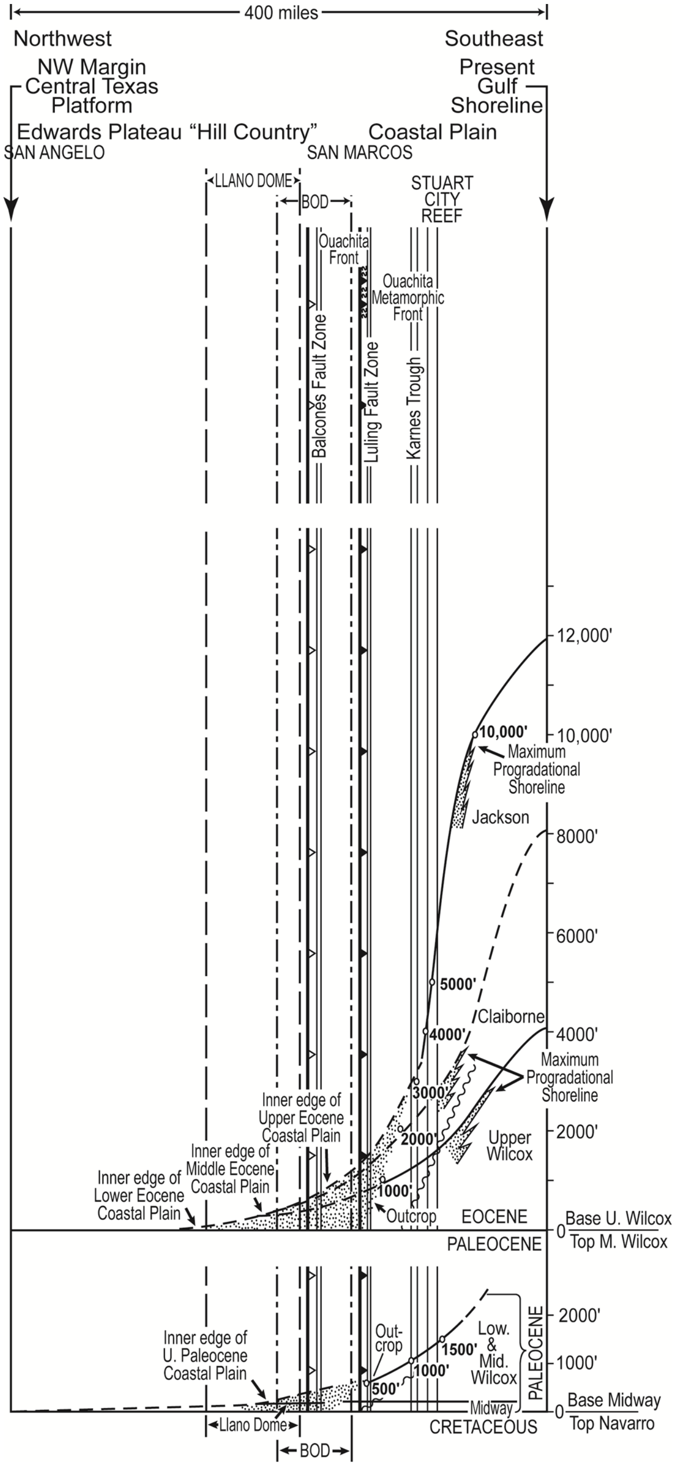


Figure 18. Projected northwest thinning of Paleocene and Eocene formations along San Marcos Arch, from the Gulf Coastal Plain across Central Texas Platform.

Blanco, and Bandera counties, perhaps reaching as far northwest as the center of the Llano Dome.

Eocene Series

Eocene formations in the Texas Gulf Coast include the upper Wilcox Formation and Claiborne, Yegua, and Jackson groups; thinning rates, projected pinchouts, and estimated maximum progradational shorelines are shown on Figure 18. All Eocene formations are characterized by extensive updip coastal plains that occupy the East Texas and Rio Grande embayments as well as the San Marcos Arch (Fig. 20). The inner edges of the early, middle, and late Eocene coastal plains display a clear regressional (offlap) pattern. Maximum progradational shorelines for the early, middle, and late Eocene commonly lie 75 to 150 miles coastward from the inner edges of their respective coastal plains, and roughly 50 miles inland from the present coastline of the Gulf of Mexico. The Eocene Series thickens regularly from the outcrop toward the Gulf of Mexico: thickness ranges from 0 to more than 10,000 feet, and contours are generally parallel to the outcrop (and the present Gulf shoreline). Based on projected thinning rates and regional isopach patterns, it seems likely that about 1000 feet of Eocene sediments were deposited over the future Balcones Fault Zone, thinning northwesterly across the Balcones/Ouachita Downwarp to pinch out over the Llano Dome.

As with the late Paleocene, Eocene coastal plain deposits (which also include fluvial and deltaic facies tracts) skirt the Edwards Plateau, so we must assume that, during the Eocene, subaerial weathering processes, including meteoric ground water, were acting on the veneer of overlying upper Cretaceous and Paleocene sediments. Whether fresh-water aquifers may also have been developed in underlying Lower Cretaceous carbonates of the Central Texas Platform (especially west and north of the Balcones/Ouachita Downwarp) is conjectural.

Upper Wilcox Formation (Early Eocene)

The updip edge of the upper Wilcox (= early Eocene) coastal plain nearly duplicates its earlier late Paleocene position, pinching out over the Balcones/Ouachita Downwarp and against the east flank of the Burro-Peyotes Arch in northern Mexico (Fig. 20). Where it pinches out on the Balcones/Ouachita Downwarp, the upper Wilcox is inferred to consist of thin, weathered coastal plain sediments and soils.

Claiborne Group (Middle Eocene)

According to Galloway et al. (2011), the middle Eocene was an extended time (10 million years) of tectonic quiescence marking the end of the Laramide Orogeny on the North American continent. Sediment supply to the northern Gulf of Mexico was notably low. Thin coastal and shelf facies prograded out onto the northern shelf of the Gulf of Mexico. Condensed intervals such as the Weches and Cook Mountain formations, reached all the way from the inner coastal plain to the abyssal Gulf of Mexico plain. Only two minor depositional episodes were recorded in the northern Gulf of Mexico: the Queen City and Sparta, contained within an overall interval of very low sediment accumulation and extensive marine inundation.

In the Rio Grande and East Texas embayments, the updip edge of the middle Eocene coastal plain shifted coastward about 50 miles, but only about 10 miles coastward over the still-positive San Marcos Arch. The maximum middle Eocene progradational shoreline lay about 150 miles southeast, near its early Eocene counterpart.

Yegua and Jackson Groups (Upper Eocene)

Sediment supply to the Gulf of Mexico Basin increased sharply in the late Eocene (Galloway et al., 2011); however, the high Yegua supply rate rapidly moderated during the latest Eocene Jackson deposition.

The location of the projected inner edge of the upper Eocene coastal plain indicates continued coastward regression, generally about 40–50 miles southeastward from the preceding middle Eocene inner edge (Fig. 20). The manifestation of the Rio Grande and East Texas embayments is, by late Eocene, almost completely gone. The maximum regressive shoreline of the upper Eocene was located about where its earlier two counterparts were, roughly 50 miles inland from the present coastline.

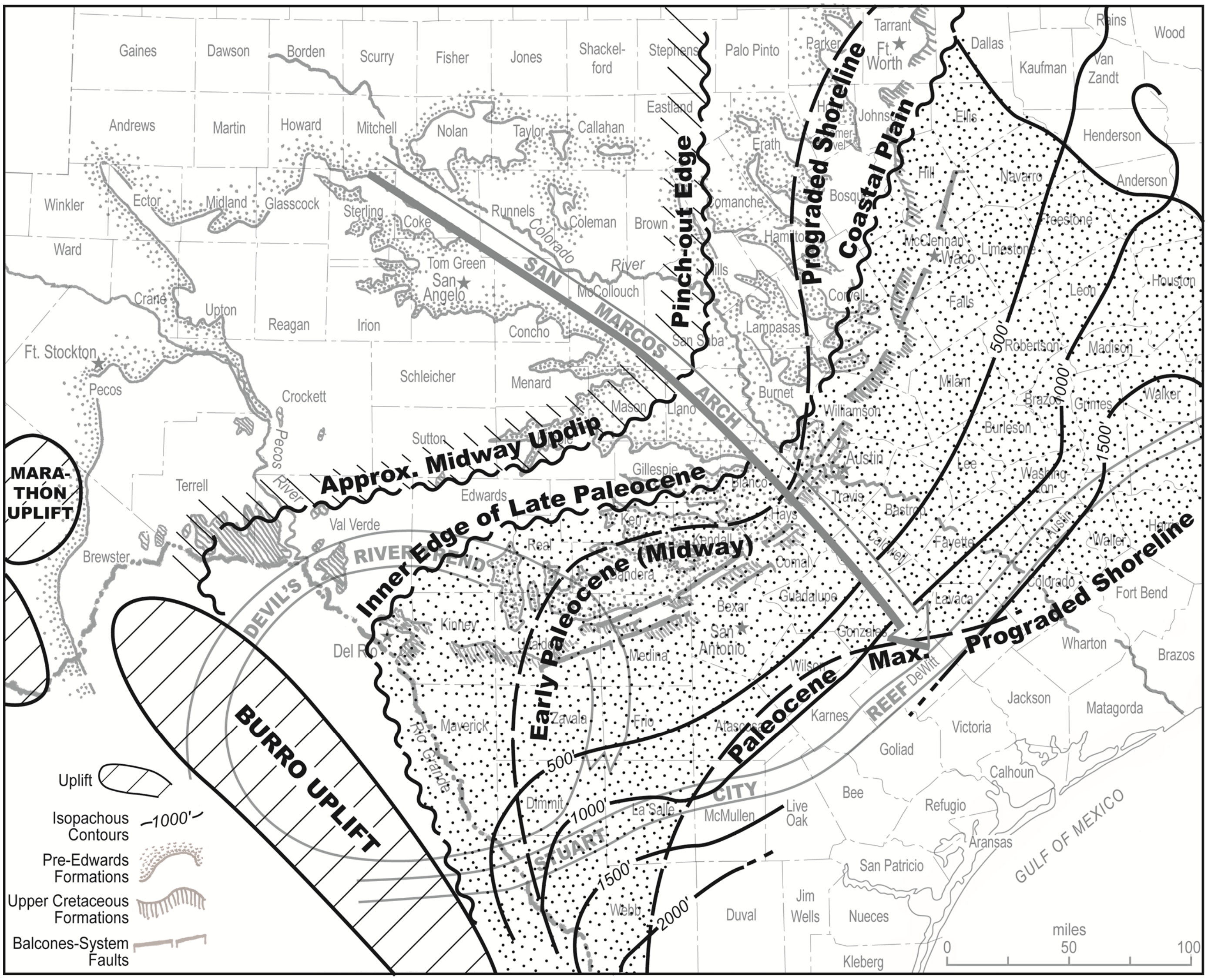


Figure 19. Paleocene isopach and depositional environments (from Cook and Bally, 1975; Galloway et al., 2011).

Oligocene Series

Galloway et al. (2011) summarize the Paleogene history of the Gulf as ending with an extended Oligocene depositional episode (10.6 million years), represented in the subsurface by the Vicksburg and overlying Frio formations. Accumulation of terrigenous sediments was highest in the first several million years, decreasing in the later Oligocene. Sediment supply rates were sufficiently high to cause extensive progradation of the entire northern Gulf of Mexico continental margin during the Oligocene.

Projected northwesterly thinning rates for the Oligocene appear on Figure 21. The putative inner coastal plain pinchout is located over the buried Ouachita metamorphic front, and the maximum progradational coastline lies under the present Gulf shoreline.

The projected inner edge of the Oligocene coastal plain (Fig. 22) exhibits the continued gulfward regression described by Galloway et al. (2011), shifting coastward 30 to 50 miles from its late Eocene counterpart. Its trend across coastal Texas has become linear, however, showing no influence of either the Rio Grande Embayment or the East Texas Basin. The maximum progradational shoreline shifts coastward correspondingly about 50 miles, coinciding roughly with the present coastline. Oligocene isopachs trend parallel with the present coastline, and show regular southeastward thickening to more than 15,000 feet near the present coastline.

Recognizing that the inner edge of the Oligocene coastal plain now lay 50 to 75 miles coastward from the now exposed and weathering sediments of the updip late Paleocene and Eocene, it seems inescapable that the buried Central Texas Platform was becoming more emergent. Soft Midway and Taylor-Navarro mudrock and Austin chalk and marl strata covering the old Central Texas Platform, were probably being subaerially weathered and eroded, as demonstrated by detrital fragments found in outcrops of late Oligocene Catahoula coastal plain sandstones 60 miles southeast from the Balcones Fault Zone, opposite the sector of greatest vertical fault displacement (Galloway, 1977). Whether or not this Upper Cretaceous cover had already been stripped away, leaving Edwards rocks exposed, is an unresolved question. If so, it is likely that ground water was infiltrating the newly exposed Edwards limestones.

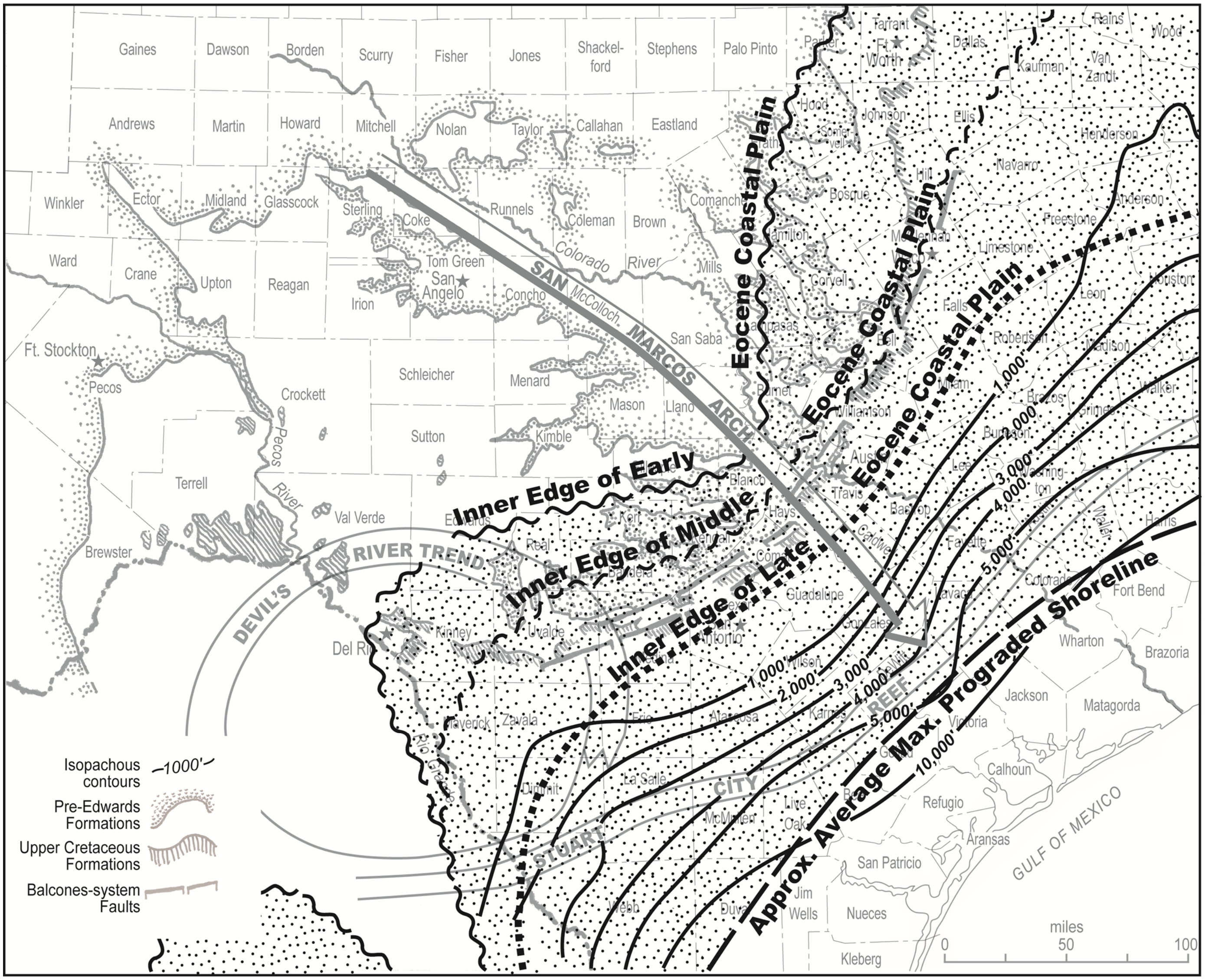


Figure 20. Eocene isopach and depositional environments (from Cook and Bally, 1975; Galloway et al., 2011).

Miocene Series

Sediment accumulation in the Gulf of Mexico during the early and middle Miocene was robust, followed by reduced accumulation during the late Miocene (Galloway et al., 2011). The inner edge of the lower, middle, and upper Miocene depositional coastal plain was consistently parallel with, and about 100 miles inboard from the present coastline, close to where it had been during the Oligocene (Figs. 21 and 23). The position of the maximum progradational shoreline advanced gulfward from the Oligocene; throughout the Miocene it remained consistently about 50–60 miles gulfward from the present shoreline. Thickness of the Miocene ranges from 0 to more than 10,000 feet; isopachous contours are generally parallel.

Maximum Balcones Faulting in Miocene

Carbonate rock fragments, including reworked Cretaceous fossils (Weeks, 1945a,b; Wilson, 1956; Ely, 1957; Ragsdale, 1960; Galloway et al., 1982) make up a substantial component of the terrigenous clastics in the fluvial/deltaic systems constituting the Miocene Oakville Formation, especially in those sectors of the Oakville outcrop opposite the Balcones Fault Zone (from Uvalde eastward to San Antonio, thence northward to Austin and Waco). Chert, presumably from the Austin and Edwards formations, is also present. This constitutes the strongest evidence for major movement of the Balcones Fault Zone during the Miocene, although Galloway (1977) noted similar but less abundant carbonate material in the Oligocene Catahoula Formation. Galloway et al. (1982) did not mention any differences in carbonate-grain abundance vertically within the Oakville stratigraphic succession, but markedly fewer carbonate rock fragments are present in Oakville sands in the Rio Grande fluvial/deltaic complex.

Ely (1957) and Ragsdale (1960) indicated that most of the reworked fossils in the Oakville are from the Austin Chalk, although Ely found some Georgetown microfossils. Also common are weathered chalk clasts, presumably from the Austin, as well as weathered clay clasts, probably eroded from Taylor-Navarro mudrocks. Weathered clasts of Buda, Georgetown and Edwards lithologies are present, but less frequent.

Balcones faulting along the medial Balcones/Ouachita Downwarp relieved growing extensional stress related to Tertiary downwarping of the Gulf of Mexico Basin. No widespread marine invasion during the Miocene in the Texas Gulf Coast succession is known that can be tied to Balcones faulting, therefore it seems that the upthrown side of the fault must have moved abso-

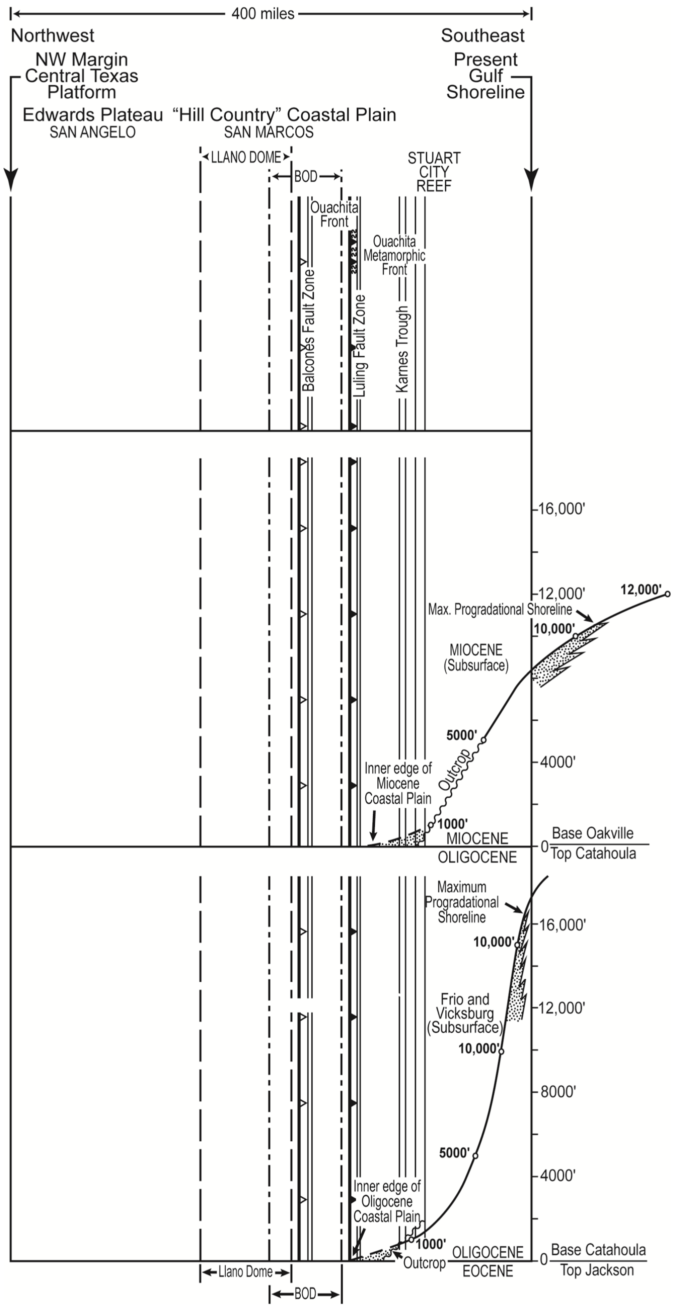


Figure 21. Projected northwest thinning of Oligocene and Miocene formations along San Marcos Arch from Gulf Coastal Plain toward Balcones Fault Zone.

lutely up (not relatively up) compared with to the downthrown side. Composite down-to-the-east structural relief (= displacement) is 1100 to 1600 feet in the Austin area (Collins and Woodruff, 2001), somewhat greater around San Antonio ("more than 500 meters" according to Ewing, 1991). Fault displacement decreases steadily to the north of Austin and to the west of San Antonio; Balcones faulting dies out about halfway between Waco and Dallas, and about halfway between Uvalde and Del Rio.

Indirect evidence has indicated periodic and minor subaerial exposure of the buried Central Texas Platform, in the area that is now the Edwards Plateau, Hill Country, and Llano Uplift, beginning with the Taylor-Navarro and continuing through the late Paleocene (lower Wilcox), Eocene, and Oligocene. The presence of detrital material and fossils recognizably derived from the Edwards, Georgetown, Buda, and Austin carbonate formations in lower Miocene sediments unequivocally demonstrates that Balcones faulting had uplifted the western and northern side of the Balcones Fault Zone, and active erosion by headward-cutting streams was now well underway, using stream-courses that may have been established by Maastrichtian or Paleocene time, especially those around the margins of the Edwards massif. Meteoric waters now began to enter exposed and faulted Edwards carbonate terranes, initiating the Edwards Underground Aquifer, and the westward-retreating landscape and drainage that nourished it.

The aggrading distributive Ogallala sedimentary apron expanded southward, as represented by the [ancestral] Pecos River alluvial system, and regional uplift of the Colorado Plateau produced a consistent regional eastward tilt of the Ogallala that also included the western Edwards Plateau, as far east as the western margin of the Llano Dome (Figs. 6 and 23).

Pliocene Series

"The Plio-Pleistocene ushered in an era of landscape evolution across the North American interior. The configuration of uplands, drainage basins, and depositional elements assumed a modern aspect" (Galloway et al., 2011). The inner edge of the Pliocene Gulf Coastal Plain paralleled the present coastline inboard about 60–90 miles (Fig. 24). The maximum progradational Pliocene shoreline lay well out in the present Gulf of Mexico, about 40 miles beyond the present shoreline. The 1000 foot Pliocene isopach contour lay 10–20 miles gulfward of the present shoreline.

The eastward and southeastward tilting of the Ogallala and western Edwards Plateau continued from the late Miocene. Unroofing of the Edwards Plateau was well underway in the Pliocene, with headward erosion dissecting the carbonate massif from the east by the ancestral Colorado and Guadalupe rivers and their tributaries, from the southwest by the San Antonio–Medina River system, and from the south by the Frio, Nueces, and Devils rivers and their tributaries. Sands and gravels at different outcrops of the Pliocene Goliad Formation provide clues about the different geological substrates in which their source-streams were operating (Maxwell,1970). Chert pebbles found in the Goliad Formation along the San Antonio and Guadalupe River valleys came from the Edwards Plateau, whereas counterpart Goliad gravels in the Colorado River valley contain, in addition to chert, pebbles of quartz, feldspar, pegmatite and associated [igneous] minerals. This indicates that the ancestral Colorado River had, by Pliocene time, cut through the Lower Cretaceous and Paleozoic carbonate formations covering the Llano Uplift, and was eroding Precambrian rocks.

Widespread deposits of high terrace gravels containing rounded cobbles and pebbles of Edwards chert and limestone, assigned to the Pliocene Uvalde Gravel (Sayre, 1936; Bennett and Sayre, 1962; Byrd, 1971), lie adjacent to the periphery of the Balcones Fault Zone, evidence of the coarse depositional aprons that were constructed marginal to the Balcones Fault scarp, at much higher topographic levels (Fig. 24). The elevations of these high gravels, thought to be related to the Uvalde Gravel, fit within a regular south-sloping surface ranging from about 2000 feet in eastern Terrell County, near the south margin of the Plateau, to about 800 feet south of Del Rio. In addition to limestone boulders and cobbles, the Terrell County high gravels are also reported to contain fragments of quartz, which indicates a source farther west and north. Especially in southwest Texas adjacent to the Rio Grande, as well as in north-Central Texas adjacent to the Brazos River drainage, Uvalde gravels contain abundant rounded cobbles and pebbles of limestone, quartz, quartzite, and various types of igneous rocks, pointing to transport from Trans-Pecos Texas, as well as the eroded margins of the Ogallala caliche in

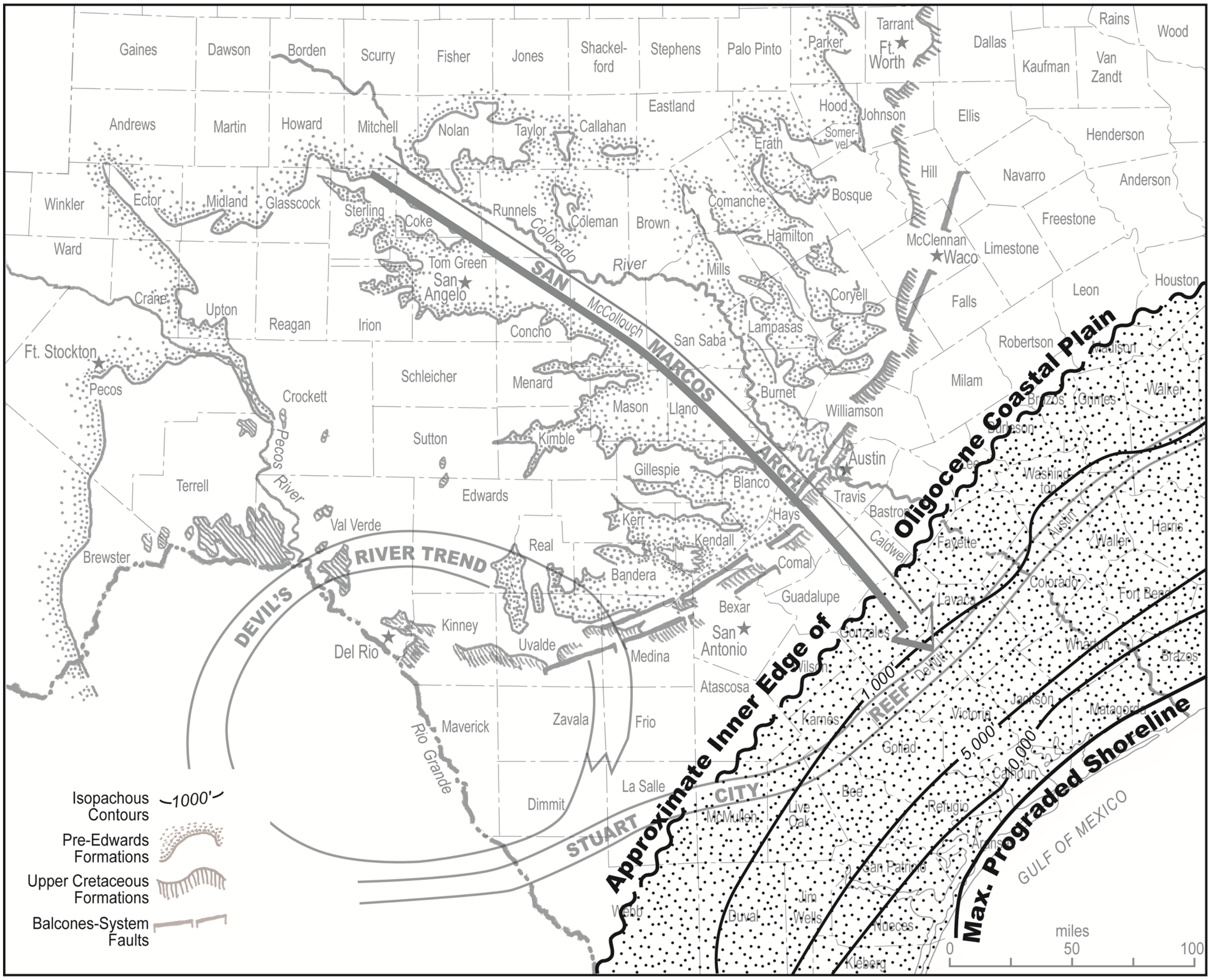


Figure 22. Oligocene isopach and depositional environments (from Cook and Bally, 1975; Galloway et al., 2011).

northwest Texas, and mixing with more locally derived sediments from the Edwards Plateau (Turner et al., 1960).

Ewing's (2005) observation should be re-emphasized here, that undisturbed Uvalde Gravels truncate and cover Balcones faults, establishing the end of the episode of Balcones faulting as pre-Pliocene.

INDEPENDENT DEPTH OF BURIAL EVIDENCE

Evidence reviewed so far has indicated that Lower Cretaceous carbonate rocks at the apex of the Edwards Plateau were never covered by more than about 1000 to 2000 feet of Upper Cretaceous and Lower Tertiary sediments, based primarily on inspection of isopach and lithofacies maps and inferred projection of such regional evidence northwestward, onto and across the Central Texas Platform. This section identifies and evaluates three independent lines of geological evidence bearing on the depth of burial question: (1) thermal maturity of Eagle Ford organic shales, (2) porosity vs. depth evidence from Cretaceous carbonate rocks in the Austin area, and (3) stylolites in Edwards and Buda limestones.

Thermal Maturity

Thermal maturity of organic-rich shales, mudstones and micritic carbonates is a function of geothermal heating by depth of burial and time (Dow, 1977; Tissot and Welte, 1978; Katz et al., 1988). The late Cenomanian-Turonian Eagle Ford Shale is a recognized petroleum source rock, for which published maturity data were available and new data were provided through the courtesy of British Petroleum Corporation (A. Donovan and A. Miceli-Romero, 2015, personal communication).

Analyses of Eagle Ford samples from five localities (Fig. 25) were evaluated: Lozier Canyon and West Comstock on the southwest margin of the Edwards Plateau, and Bouldin Creek and Austin Community College (ACC) in Austin (all surface or very shallow localities), plus subsurface data from three wells in the First Shot Field, DeWitt, Gonzales, and Wilson counties, depths ~7235 to 9234 feet (Edman, 2012). Table 1 summarizes these data.

Recognizing that unknown thicknesses of overlying formations had been stripped away from the Eagle Ford near the Balcones Fault Zone, the writer originally hoped that thermally immature Eagle Ford samples from the outcrop could be used to estimate their maximum depth of burial. This could have provid-

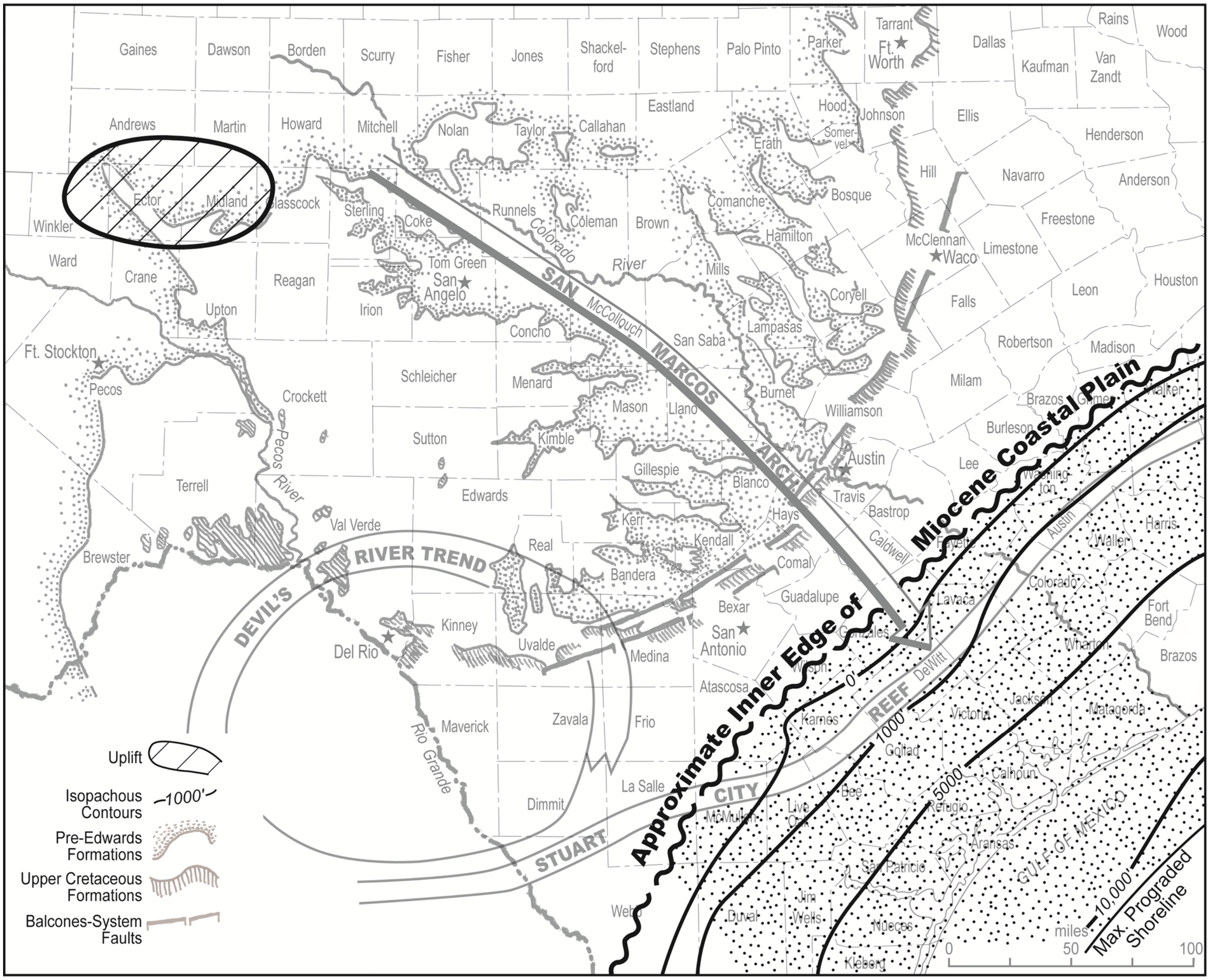


Figure 23. Miocene isopach and depositional environments (from Cook and Bally, 1975; Galloway et al., 2011).

ed an independent means of supporting or challenging the estimated thickness of Upper Cretaceous and Tertiary strata at the margins of the Edwards Plateau/Llano Uplift/Hill Country sector of the Central Texas Platform, which had been derived by projection of interval thicknesses of Upper Cretaceous and Tertiary formations adjacent in the subsurface under the Gulf Coastal Plain (sections IX and X). Unfortunately, the anticipated precision of such depth of burial estimates based on thermal maturity has proved disappointing, because of a number of factors:

(1) Eagle Ford shales, being mostly marine, contain kerogen that is deficient in vitrinite (Edman, 2012; B. Katz, 2016, personal communication), thus rendering vitrinite reflectance (Ro) values suspect;
(2) Substantial variations in Eagle Ford lithofacies appears to affect derived pyrolysis (Tmax) and Ro calculations (Edman, 2012; Donovan et al, 2012);
(3) There is no assurance that late Cretaceous and Tertiary geothermal gradients were similar to present geothermal gradients;
(4) Tmax values range widely among many samples from the ACC, Bouldin Creek, Lozier Canyon, and First Shot localities;
(5) Correlation of common thermal maturity measures (Ro and Tmax) is poor among immature samples (Hunt, 1996, after Peters, 1986);
(6) Correlation of Tmax values with depth becomes increasingly variable with diminishing thermal maturity;
(7) Present-day variations in geothermal gradient among the five different localities compromise direct comparisons; and
(8) Among outcrop samples, there is no apparent correlation between present geothermal gradient and Tmax—locations with high geothermal gradient show low Tmax values, and low geothermal gradient locations have higher Tmax values. This probably reflects variable weathering of surface samples.

Taking all these factors into account, the author has nevertheless developed a crude method for estimating the approximate depth of burial of the four surface localities. Where multiple Tmax values (the leading method for determining thermal maturity based on pyrolysis) have been determined from different depths in a single well, or from the same source rock formation in different wells at different depths (especially where Tmax values vary widely, from immature to mature and even into the

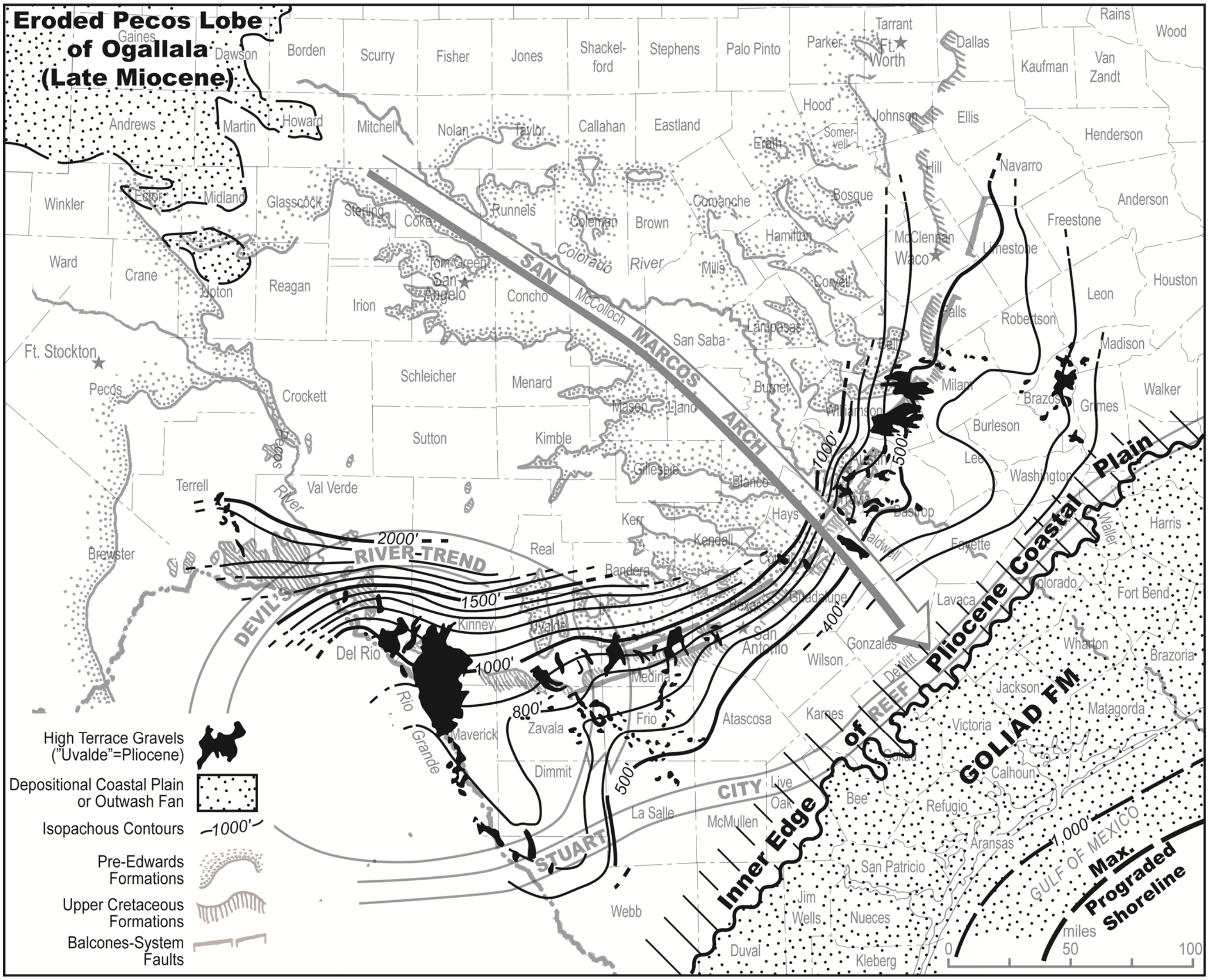


Figure 24. Pliocene isopach and depositional environments, with generalized structure on base of Uvalde Gravel and equivalent high terrace gravels (from Cook and Bally, 1975; Galloway et al., 2011; Texas Bureau of Economic Geology, Geologic Atlas of Texas (Austin [1974], Crystal City–Eagle Pass [1976], Del Rio [1977], Fort Stockton [1982], Laredo [1976], San Antonio [1983], Seguin [1974], Sonora [1981], and Waco [1970] sheets).

gas range), construction of a thermal maturity vs. depth profile is straightforward. That is not the case here.

The first step (Fig. 26) was to plot the depth vs. Tmax profile for two Eagle Ford wells in the First Shot Field, where Tmax and depth are known (Edman, 2012). Tmax values from the deepest First Shot well (Robinson-Troell #1) were not used, inasmuch as Edman found them to be anomalously hot, compared with the other two nearby wells (Ball-Sample #1, average sample depth 7293 feet; Estrada et al #1, average sample depth 8756 feet). As shown by Dow (1977) and Hunt (1996), depth vs. Tmax profiles follow a semi-log distribution (depth is Cartesian; Tmax or Ro is logarithmic), so the profile assumes a straight sloping line. Note that the value of Tmax projected to the surface would approach 400—a value slightly above the anticipated lower limit of about 390 for an immature sample (B. Katz, 2016, personal communication).

The next step was to plot the median Tmax values of the four surface samples (Bouldin Creek [BC], Austin Community College [ACC], Comstock West [CW], and Lozier Canyon [LC]) on the constructed First Shot profile (Fig. 26). This allowed a depth to be assigned to each Tmax of the four surface localities; the problem now was that the geothermal gradients of the four surface localities and the First Shot Field, even though plotted on a common geothermal gradient (First Shot Field), were all different.

The third step was to determine the geothermal gradient for each of the four surface localities and the First Shot Field (DeFord and Kehle, 1976), post the depths of each of the four surface localities on the geothermal gradient profile of the First Shot field, and derive the subsurface temperature associated with that depth (Fig. 27).

The fourth and final step was to plot geothermal gradient profiles for each of the four surface localities on the same diagram with the First Shot Field geothermal gradient, and post on each profile the depth associated with that subsurface temperature (Fig. 27).

Results of this procedure should be viewed with caution, in view of the attending assumptions and uncertainties. Nevertheless, it seems possible to draw some general conclusions about Eagle Ford depth of burial marginal to the Balcones Fault Zone:

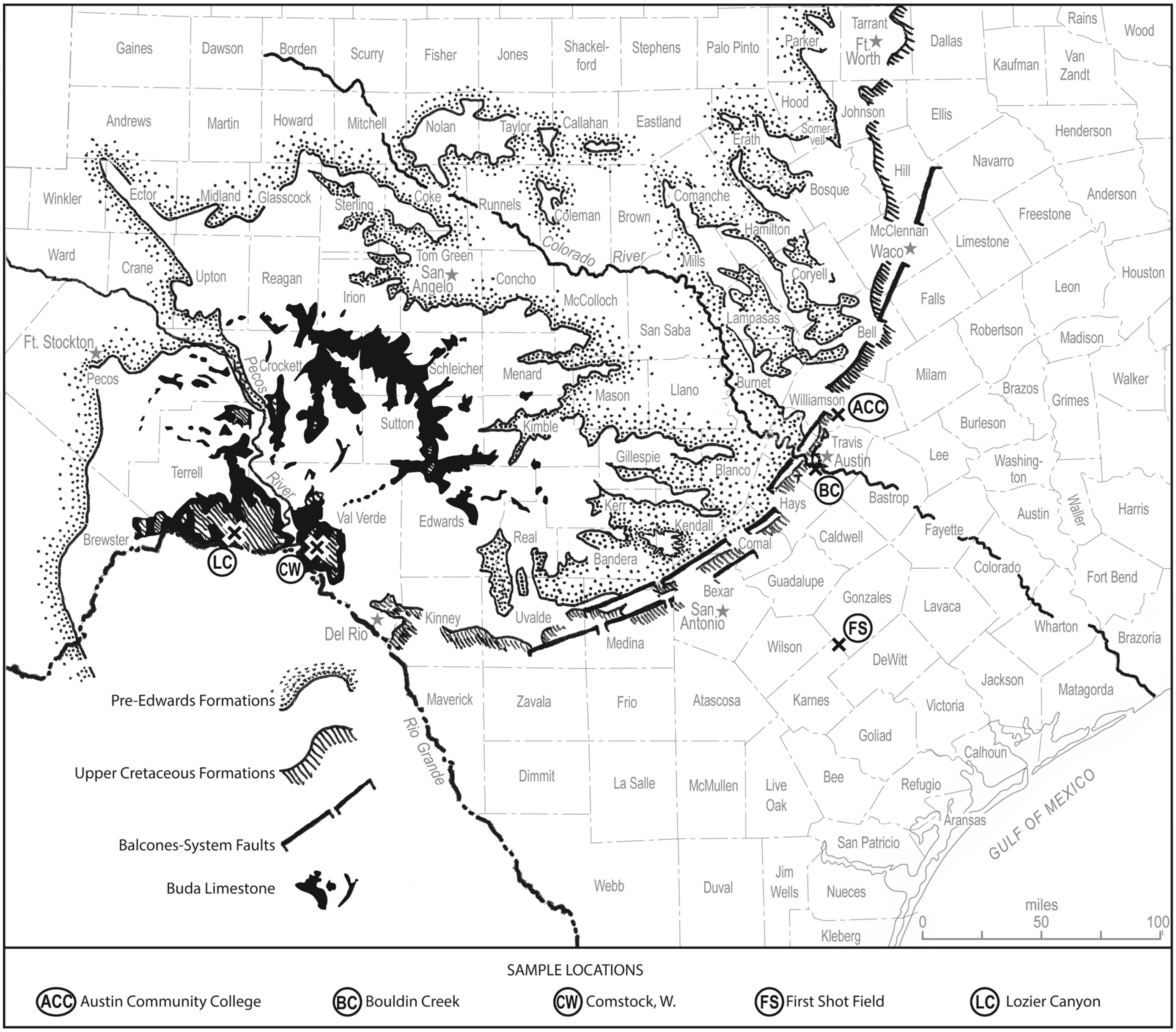


Figure 25. Locations of Eagle Ford and Boquillas samples for depth of burial study; A. Donovan and A. Miceli-Romero, 2014, 2015, personal communication; also Donovan et al., 2012).

(A) Eagle Ford samples from all four localities adjacent to the Balcones Fault Zone are thermally immature; none are anywhere close to the recognized thresholds for thermal maturity (0.6 Ro and 435°C Tmax).

(B) Using the First Shot Field samples for comparison, where the depth threshold for thermal maturity occurs at about 7200 feet (Tmax 432–448°C; median = 442°C), all four surface localities are significantly immature (Bouldin Creek Tmax median = 420°C; Austin Community College borehole Tmax median = 423°C; Comstock West roadcut Tmax median = 426°C; and Lozier Canyon outcrop Tmax median = 433°C).

(C) A cross-plot of depth vs Tmax (Hunt, 1996) shows Tmax 430°C correlating with a depth of 1640 feet, but no geothermal gradient is shown.

(D) Taking all data into account, it appears that Eagle Ford strata at the Bouldin Creek locality in Austin had a depth of burial of perhaps 2850 feet, within the one-standard deviation range of 2000–5500 feet. The Eagle Ford at the Austin Community College location, about 15 miles northeast of Bouldin Creek, was buried between 2200 and 4300 feet, with a median of about 3500 feet. Depth of burial of the West Comstock Eagle Ford was probably between 4400 feet and 5500 feet (best estimate is 5000 feet). The Lozier Canyon Eagle Ford was buried between 6000 feet and 7800 feet, with a median of about 7350 feet.

(E) By comparison, overburden thicknesses derived from isopach mapping and derivative projected northwesterly thinning diagrams (Figs. 14, 18, and 21) suggest that the Eagle Ford around New Braunfels (on the crest of the San Marcos Arch) was buried under about 2000–2300 feet of Upper Cretaceous and Tertiary sedimentary rocks: Upper Cretaceous—Austin, 300–350 feet; Taylor-Navarro, 700–800 feet; Paleocene—Midway, 150 feet; lower and middle Wilcox, about 300 feet; Eocene—500–700 feet. Taking into account Austin's location 40 miles off-flank to the San Marcos Arch, this is compatible with depth of burial estimates (Bouldin Creek [2000 to 5500 feet; median =

Table 1. Data on Eagle Ford samples used for estimating depth of burial (data provided by A. Donovan and A. Miceli-Romero, 2014, 2015, personal communication).

LOCALITY		DEPTH (FT)	NO. SPLS	Ro (%)	SOURCE	Tmax (°C)	GEOTHERMAL GRADIENT (°F/100')	THERMAL MATURITY
Bouldin Creek (BC) **Austin**		surface 0-25	29	0.45	Liro et.al. 1994	411-434 md 420	1.4	Immature Ro Immature Tmax
Austin Community College (ACC) **Austin, ~15 mi NE of EC**		80-125 shallow well	10	NR	Miceli Pers. Corr. 2015	417-429 md 423	1.5	Immature Tmax
Comstock West (CW) **~5 mi W of Comstock, TX** **NW Valverde Co., TX**		surface roadcuts	8	0.53	Slatt, et.al. 2012	423-429 md 426	1.25	Immature Ro Immature Tmax
Lozier Canyon (LC) **Exreme E. Terrell Co., TX**		surface 20-187	30	NR	Miceli Pers. Corr. 2015	428-438 md 433	1.2	Immature Tmax
First Shot Oil Field (FS) **DeWitt, Gonzales, Wilson Cos., TX**								
Bell-Sample #1 Well	core samples	7235-7353 avg 7293	14 7	0.59 (?)	Edman 2012	432-448 md 440	1.55	Early Oil Window (Ro) Early Oil Window (Tmax)
Estrada, et.al. #1 Well	samples	8640-8785 avg 8756	10	1.15-1.21 (?)	Edman 2012	444-447 md 445.5	1.55	Late Oil Window (Ro) Peak Oil Generation (Tmax)
Robinson & Troell #1 Well	core	9220-9250 avg 9234	4	1.06-1.21 (?)	Edman 2012	451-454 md 452.5	1.55	Late Oil Window (Ro) Late Oil Window (Tmax)

2850 feet]; and Austin Community College [2200 to 4300 feet; median = 3300 feet] derived from thermal maturity calculations. By comparison, a structural reconstruction introduced subsequently in this paper (Fig. 28) indicates Eagle Ford depth of burial at New Braunfels to be about 2300 feet.

(F) The corresponding depth of burial estimates for the two southwest Texas localities (Comstock West [4400 feet to 5500 feet; median = 5000 feet] and Lozier Canyon [6000 to 7800 feet; median = 7350 feet]) are significantly greater than the two Central Texas localities, indicating deeper burial. Suggested explanations may be: (1) thicker sections of Taylor-Navarro deltaic and shallow-marine terrigenous clastics, and/or fluvial-alluvial Paleocene and Eocene clastics derived from the southern Rocky Mountain Province, both now removed by erosion during and after the Laramide Burro Uplift; and/or (2) a higher geothermal gradient in the latter two localities in the geological past; this explanation may be supported by work of Cardneaux and Nunn (2013), which showed the threshold of Eagle Ford oil generation in western Kinney County (about 40 miles southeast of the West Comstock and Lozier Canyon localities, and similarly close to the Rio Grande) to be unusually shallow, at depths of 1000–2000 feet.

Porosity vs. Depth Trends in Lower Cretaceous Carbonates

On the basis of (1) thickness of estimated Upper Cretaceous and Paleogene cover, (2) measured porosity of Glen Rose and Austin Chalk carbonate rock samples; and (3) isolated geothermally-based subsurface depth-projections, Fullmer and Lucia (2006) challenged a commonly-held geological view that Cretaceous carbonates in the area of the Balcones Fault Zone in the Austin-San Antonio corridor had been buried no more than 2000 feet. They concluded that the base of the Cretaceous has been buried 6000 to 8000 feet in that area. Adjusting for the interval thickness from the base of the Cretaceous to the Eagle Ford (1700 feet), the equivalent values would be 4300 to 6300 feet for Eagle Ford depth of burial in the Austin area, values that are significantly higher than depth of burial estimates presented here.

In particular, they showed that carbonate samples from the Glen Rose Formation in Austin had average porosity of 15 percent, which corresponded to a depth of burial of about 7500 feet, based on a porosity-depth curve published by Schmoker and Halley (1982). However, substantial variation ("scatter") of observed porosity-depth values characterizes the Schmoker and Halley porosity-depth curve from the surface to depths in excess of 18,000 feet. For example, the full range of sample depths centered around 15 percent porosity ranges from about 2700 feet to 11,500 feet. Moreover, Fullmer and Lucia (2006) provided no data as to the number of Glen Rose samples they analyzed, or the full ranges of measured porosities, and they did not make projected thinning diagrams of Cretaceous and Tertiary formations or otherwise try to estimate shelfward thinning rates based on independent stratigraphic data.

Also, samples from the Austin Chalk indicated burial depth of about 5000 feet (actually, 4660 feet) around Austin, based on a burial curve published by Scholle (1977). Inasmuch as only about 1000 feet of section separate the Glen Rose from the Austin, there is an obvious discrepancy, which Fullmer and Lucia (2006) related to differences in geothermal gradients, hardly a compelling explanation. They offer no information as to sample sizes or ranges of sampled stratigraphic interval, nor do they indicate that samples were taken over a wider stratigraphic range, from the overlying Buda, Georgetown and Edwards, or underlying Cow Creek limestones.

The Austin Chalk depth of burial suggested by Fullmer and Lucia (4660 feet) falls within the upper part of the full range of the Bouldin Creek (1050–6500 feet) and Austin Community College (1800–4700 feet) Eagle Ford samples, whereas their Glen Rose depth of burial is clearly well beyond the upper bound of range, even allowing for the ~1000 foot interval thickness between Glen Rose and Austin Chalk. Furthermore, structural reconstruction across the Balcones Fault Zone (Fig. 28), indicate that the Eagle Ford Formation in the New Braunfels area was buried 2000–2300 feet beneath the Austin, Taylor, Navarro, Midway, Wilcox, Claiborne, Yegua, and Jackson formations. Depth

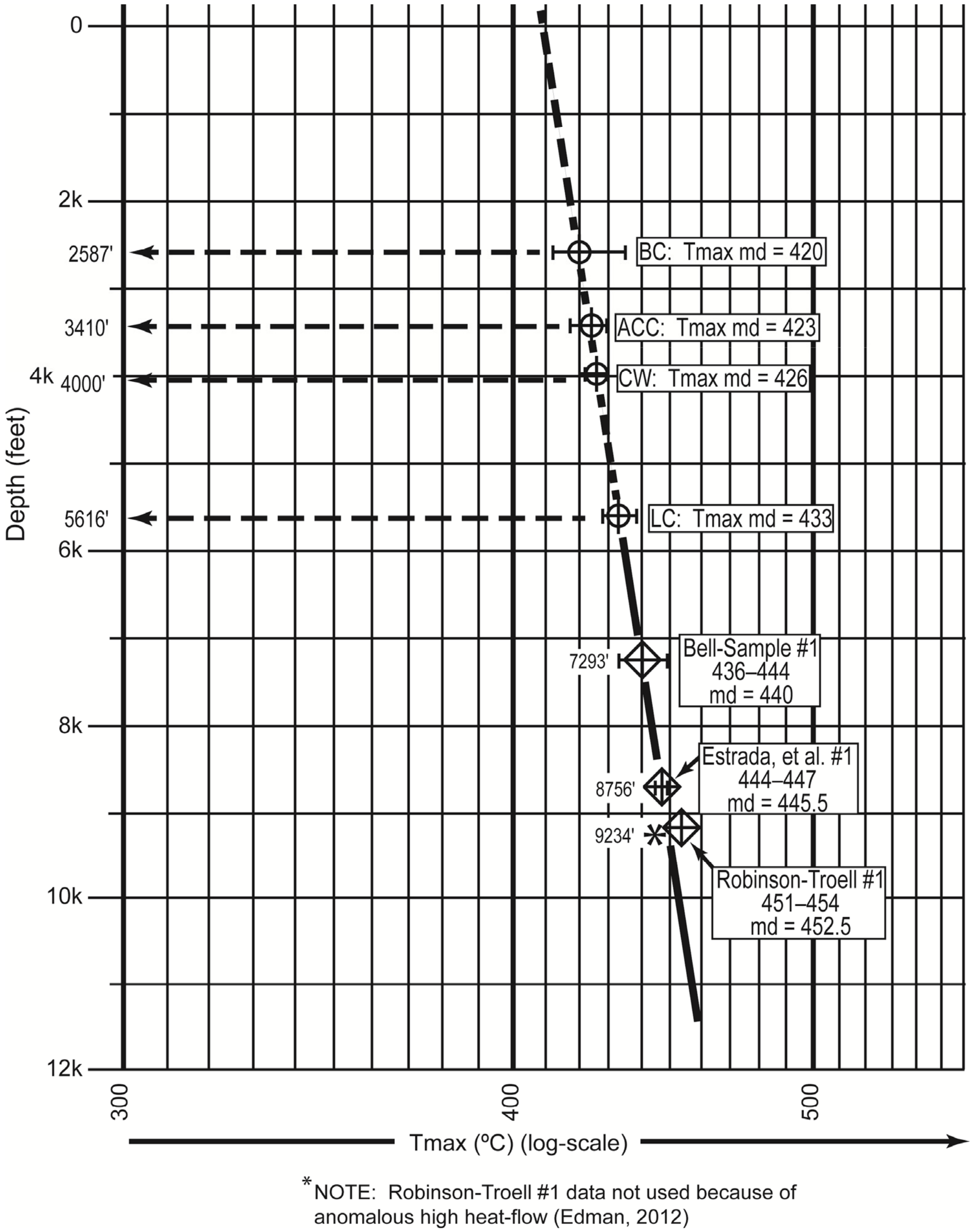


Figure 26. Tmax of surface samples (Eagle Ford Formation) plotted on subsurface depth vs. Tmax profile. First Shot Field, Central Texas (after Edman, 2012; A. Miceli-Romero, 2015, personal communication).

of burial of the Eagle Ford in the Austin area—about 40 miles downflank from the axis of the San Marcos Arch—was probably somewhat greater, estimated as about 2850 feet.

Compaction

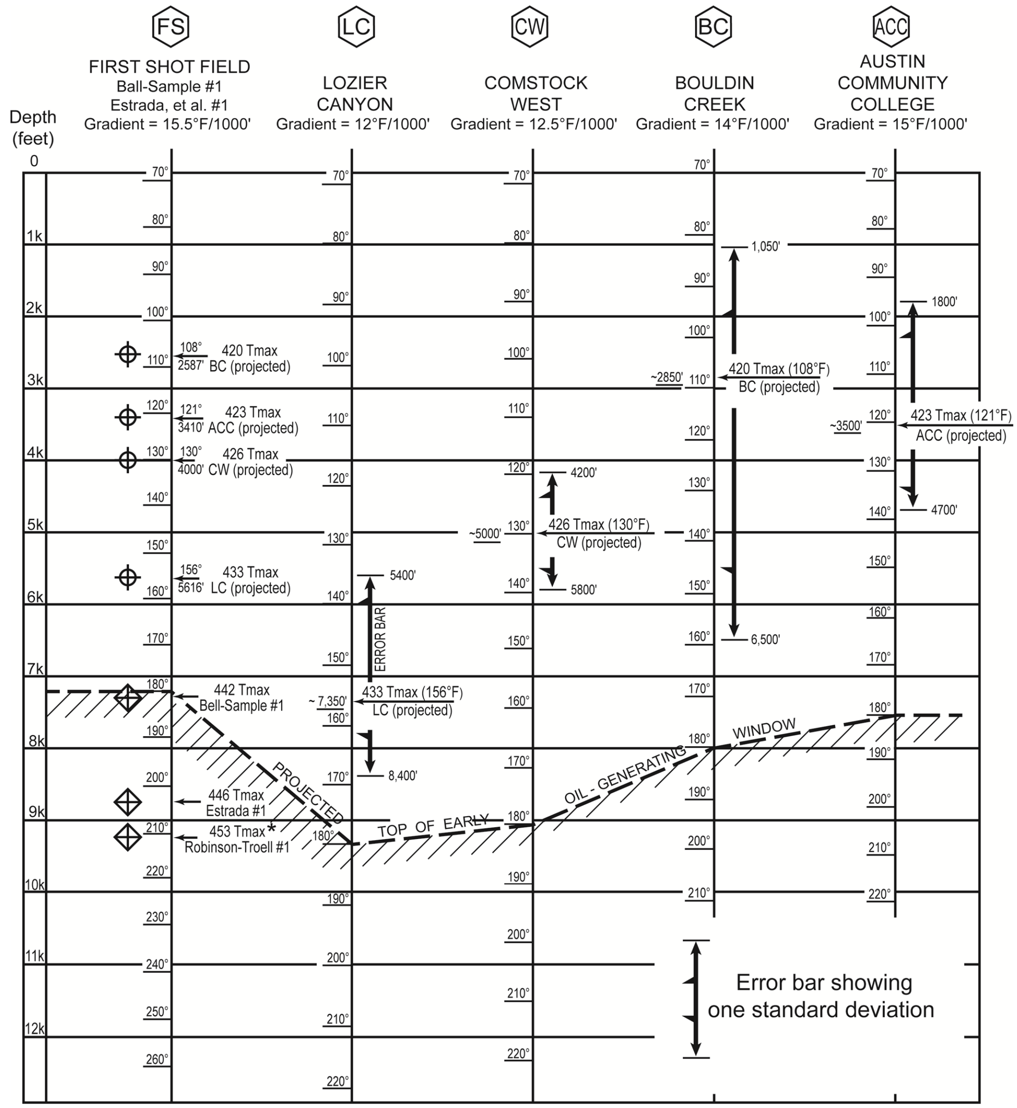
As shown by Shinn and Robbin (1983), lime mud (micrite) compacts much like shale or mudstone, inasmuch as pressure increases with added overburden, even relatively small thicknesses of overlying layers. Edwards micrites from the Edwards Plateau show evidence of modest compaction, especially the characteristic wispy nodular marly micrites. Skeletal carbonate sediments show much less tendency for compaction, retaining rock fabrics very similar to that of the original sediment. So compaction itself provides very little diagnostic evidence bearing on depth of burial of Edwards carbonates. Much more compelling evidence is, however, provided by another feature of buried carbonate rocks—stylolites.

Stylolites

Stylolites are jagged, interdigitate surfaces, usually in homogeneous carbonate rocks, in which the irregularities of the two sides fit into each other. They typically occur parallel to the bedding. Stylolites are generally thought to form diagenetically, indicating differential vertical movement by solution of carbonate rocks under pressure. Clay, carbon, or iron oxides are concentrated along the irregular seams as residues after solution of carbonate rocks.

According to Bathurst (1995), geologic conditions required for stylolites to form are: (1) Meteoric recharge to yield an aquifer in which calcite cement can be precipitated, (2) sufficient supply of dissolved calcium carbonate ions for precipitation of cement, (3) low hydrostatic pressure of pore water (i.e., no overpressuring), (4) retention of enough porosity to provide a sink for precipitation of pressure-dissolved calcium carbonate, (5) sufficient depth of burial for adequate stress (~2000–3000 feet), and (6) sufficient time for stylolites to grow.

Figure 27. Projected depth of burial of four Eagle Ford–Boquillas surface samples based on subsurface depth vs. Tmax profile, First Shot Field (Eagle Ford Formation), Texas, adjusted for geothermal gradients of surface localities.



Stylolites are common in subsurface Edwards rocks on the San Marcos Platform. They are notably uncommon in Edwards rocks that crop out on the Edwards Plateau, and present only as incipient, very low-amplitude carbonaceous surfaces in wispy nodular marls and micrites, indicating they have not been buried by more than ~2000–3,000 feet) of overburden, even though Bathurst's other five requirements would seem to be satisfied. Their general absence on the Edwards Plateau provides independent evidence supporting the very shallow burial history of Edwards carbonates on or near the axis of the San Marcos Arch.

SUMMARY

The Late Cretaceous and Tertiary burial history of Central Texas derives from a synthesis of the geological events that followed deposition of the Edwards Group and associated limestones. Many conclusions are inferred or even speculative, based on sparse, equivocal, often secondary evidence. Geological judgment and experience have been relied upon in the face of sparse or seemingly undiscoverable facts. Integration of all facts and interpretations is represented by Figure 28, a NW–SE geological cross-section along the axis of the San Marcos Arch, from the western part of the Central Texas Platform to the mid-dip sector of the Gulf Coastal Plain, at the end of the Eocene epoch. Counterpart Figure 29 is a cross-section along the same traverse, showing present-day geology and landscape, after Balcones faulting and subsequent dissection. Strata that have been removed by erosion are shaded.

In a simplistic way, the post-Edwards history of the region can be divided into three general stages:

(1) Concluding the Comanchean Epoch, the thin (<50 feet) widespread, pelagic, lower Cenomanian Buda Limestone was deposited over the vast Albian carbonate bank of the Central Texas Platform. After a brief but widespread episode of subaerial exposure, the Platform was mantled under a blanket of Upper Cretaceous (Eagle Ford [= Boquillas] organic shales and siltstones, Austin Chalk, Taylor-Navarro mudrocks and marls), and lower Paleocene (Midway) soft marine marls and mudrocks. Accumulation of these strata was interrupted by frequent periods of exposure and nondeposition (~37 million years).

(2) The buried carbonate massif began to be slowly uplifted so that upper Paleocene, Eocene, and lower Oligocene formations thinned onto, and pinched out across, the Balcones/Ouachita Downwarp. This allowed partial erosion of the thin veneer of contemporary unconsolidated terrigenous inner coastal plain clastics as well as some of the underlying mantle of soft marine lower Paleocene and Upper Cretaceous marls and muds (~34 million years).

(3) Increasing uplift of the Central Texas Platform during the late Oligocene and Miocene culminated in Balcones faulting. Carbonate strata of the widespread Edwards Group

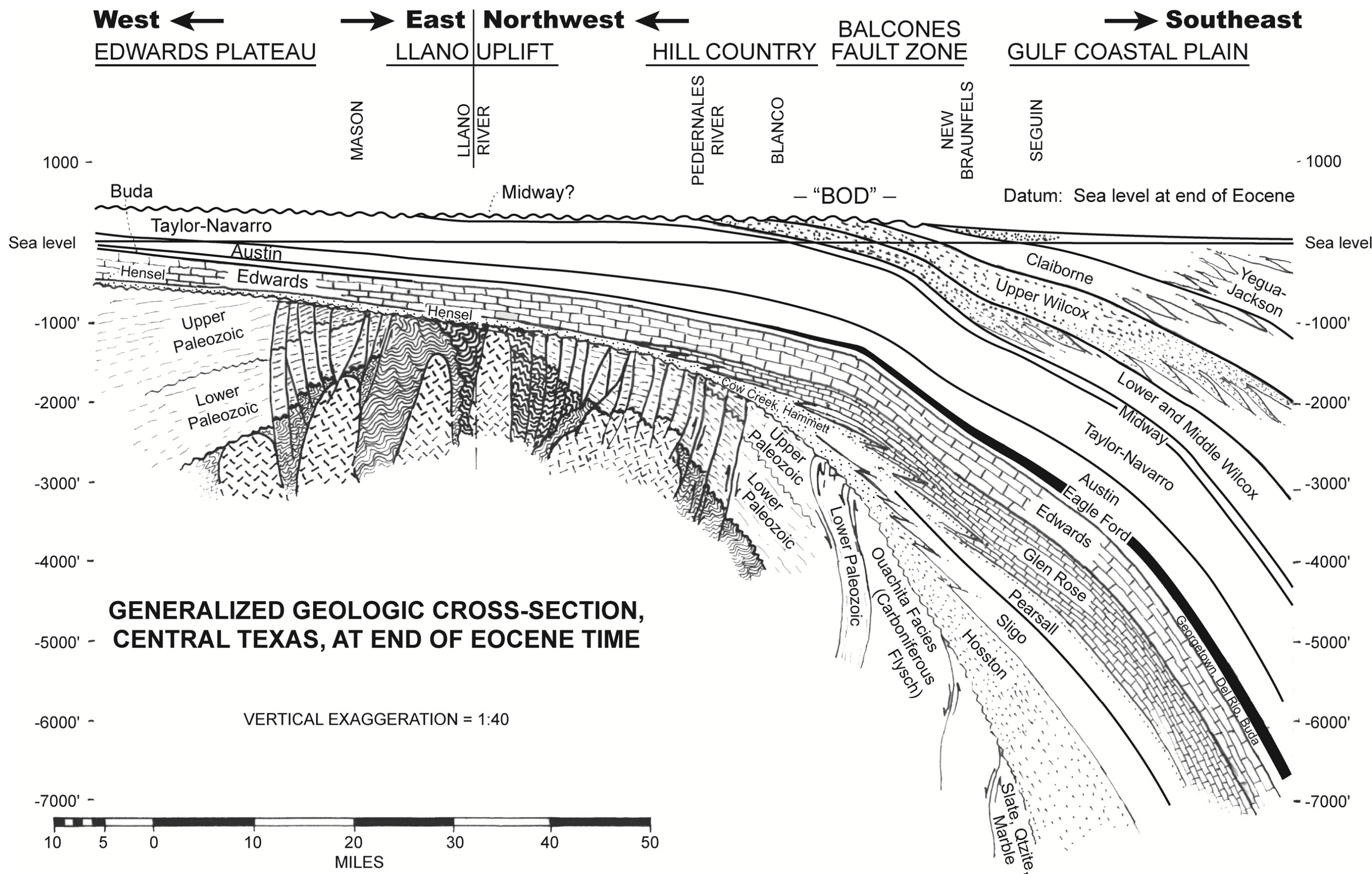


Figure 28. Generalized geologic cross-section, Central Texas, at end of Eocene time; datum = Eocene sea-level.

were subaerially exposed, and headward erosion of the elevated and undissected carbonate rock mass began, by streams flowing east and south. Pliocene southeastward tilting and progressive headward erosion of the Hill Country, Llano Uplift, and Edwards Plateau followed, leading to the present geomorphic stage of landscape evolution (~28 million years).

Late Cretaceous and Tertiary Burial History of Central Texas

Cenomanian

The Del Rio Clay (Fig. 10) represents a geologically brief period marked by widespread deposition of lower Cenomanian smectitic clays during a shallow marine invasive pulse. A very thin (<20 feet) Del Rio may have covered the Hill Country and Llano Uplift, but is absent over most of the northern and western Edwards Plateau, either by onlap at the base or truncation beneath the overlying Buda Limestone, a thin (<40 feet), very widespread, pelagic lime mudstone that blanketed all but the northern 20% of the Plateau, where it was truncated by brief and gradual uplift to the north and west (Fig. 11). Intermittent marine flooding over the crest of the Central Texas Platform by late Cenomanian Eagle Ford–Boquillas seas left a thin veneer of dark organic-rich mudstone and carbonate siltstone less than 30 feet thick (Fig. 15).

Coniacian–Santonian–Early Campanian

The Austin Chalk is about 350 feet thick between Austin and New Braunfels, across the axis of the San Marcos Arch (Fig 16). The Dessau Formation, the most marine of the Austin Group, is probably the only Austin-equivalent that would have extended across the axis of the Central Texas Platform, thinning to about 200 feet or less. Austin equivalents thicken to about 500 feet in the East Texas Basin, the Rio Grande Embayment, and the ancestral Gulf of Mexico Basin seaward of the Stuart City Reef, and as much as 1000 feet in the Chihuahua Trough. It is likely that the blanket of Austin Chalk may have begun to mute the depositional topography on the flanks of the positive Central Texas Platform, but probably did not obliterate it.

Late Campanian–Maastrichtian

Although the Campanian and Maastrichtian represent gradual regional regressions after the Coniacian-Santonian maximum flooding event, the Taylor and Navarro formations of the upper Texas Gulf Coast are about 1000 feet thick southeast of Austin and about 800 feet thick southeast of New Braunfels (Fig. 17). Almost all of the Taylor is marine; much of the Navarro is marine, especially the Corsicana Marl. It is, therefore, probable that at least some Taylor-Navarro sediments were deposited on the Central Texas Platform, perhaps ranging from 400 to 800 feet thick, of which the Corsicana (lower Maastrichtian) probably represents the only marine cratonic transgression in that sequence capable of extending far to the northwest along the San Marcos Arch, completely across the Central Texas Platform. Perhaps 100–400 feet of Corsicana may have been deposited over the buried Llano Dome, thinning westward.

Navarro shallow-marine sand bodies are present in the East Texas Basin and across the mid-dip sector of the San Marcos Platform. In the Rio Grande Embayment, upper Taylor/lower Navarro shallow-marine carbonate deposition (Anacacho) was followed by three shoaling-upward deltaic to shallow-

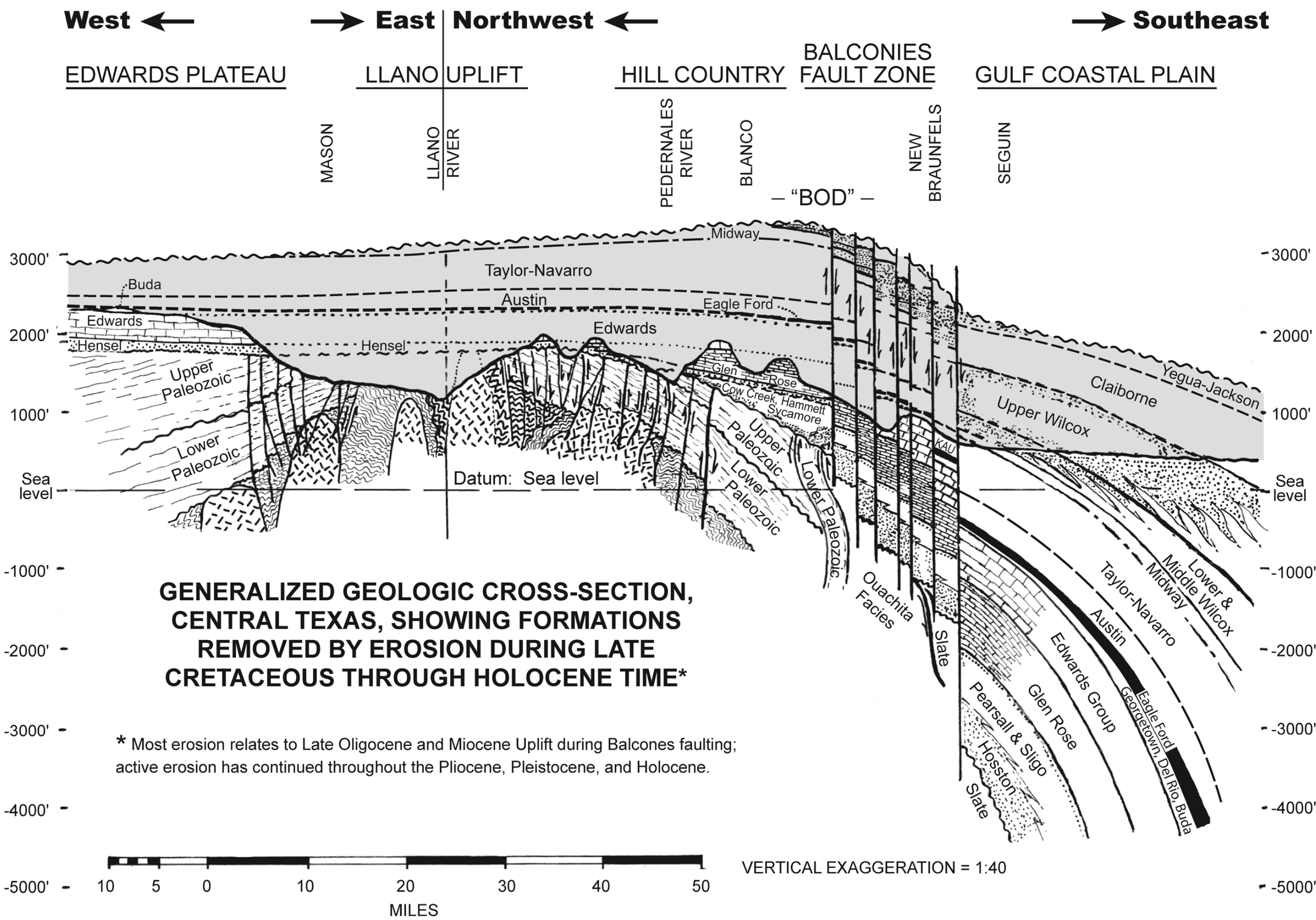


Figure 29. Generalized geologic cross-section, Central Texas, at present time, showing formations removed by Late Cretaceous through Holocene erosion; datum = modern sea-level; shaded area shows geologic section removed by post-Eocene erosion.

marine sand formations: the San Miguel, Olmos, and Escondido[4]. These sand formations indicate that the Central Texas Platform—adjacent to the north and mantled by soft Upper Cretaceous chalks and marls—must have been subaerially exposed periodically during the late Campanian and Maastrichtian.

Early Paleocene

The Midway Formation represents the last marine pulse onto the Comanche Shelf before the onset of Tertiary clastic regressional deposition southward into the Gulf of Mexico Basin. Dark marine mudstones reached far onto the Central Texas Platform, with the maximum progradational shoreline bending around the eastern margin of the Llano Dome (Fig. 19). Midway sediments to the west and north were probably shallow marine sand, silt, and mud, grading westward to a very thin apron of low-energy coastal plain terrigenous clastics that probably did not reach beyond the present western margins of the Edwards Plateau (Fig. 28). The Midway was probably about 200 feet thick over the Balcones/Ouachita Downwarp, and perhaps 100 feet thick over the west side of the Llano Uplift.

Late Paleocene–Eocene

The lower and middle Wilcox (upper Paleocene) initiated the characteristic Gulf Coast model of regressional terrigenous clastics grading gulfward from coastal plain and deltaic settings into increasingly marine environments, a depositional pattern that would continue, with variations, throughout the Tertiary (Figs. 19 and 20). Because of gulfward subsidence, the subsurface Central Texas Platform was now completely covered by younger strata (Fig. 27). A wide apron of coastal plain sediments extended over the subsurface San Marcos Arch and into the Rio Grande Embayment. North of the San Marcos Arch, the inner (updip) edge of the lower and middle Wilcox coastal plain trended northward, overlying the Balcones/Ouachita Downwarp. South of the San Marcos Arch, it deflected west, reaching across the southern margins of the buried Central Texas Platform to near present Del Rio. Lower and middle Wilcox sands probably thinned northwesterly across the Balcones/Ouachita Downwarp, from ~300 feet to zero.

This basic pattern continued throughout the Eocene (upper Wilcox, Claiborne, Yegua, and Jackson groups, respectively, as shown by Figures 18, 20, and 27). The position of the inner edge of the upper Wilcox coastal plain was similar to its earlier counterpart in the lower and middle Wilcox. For the Claiborne Group (middle Eocene) the inner edge of the coastal plain shifted about 50 miles coastward, but still a few miles northwest of the future Balcones Fault Zone. The late Eocene (Yegua and Jackson) coastal plain shifted farther coastward, so it traversed the mid-dip sectors of the Rio Grande Embayment and East Texas Basin.

[4]The broad analogy with the well-known Upper Cretaceous terrigenous clastic regressions of the southern Rocky Mountain Province (Mesa Verde, Pictured Cliffs, and Fox Hills) cannot be ignored (King, 1959; Weimer, 1960).

Across the subsurface San Marcos Arch it lay just southeast of the future Balcones Fault Zone.

Eocene inner coastal plain sands may have been as much as 800 feet thick along the future Balcones Fault Zone, thinning abruptly to the west and north. Probably no more than a few hundred feet of Eocene inner coastal plain terrigenous clastics ever extended onto the Llano Dome, and none extended westward beyond it. As later Tertiary gulfward regression progressed, those unconsolidated clastic sediments would have been the first to have been eroded from the slowly emerging massif above the buried Central Texas Platform. Inasmuch as all Eocene inner fluvial-plain sedimentation took place above Eocene sea-level, the strata overlying the buried carbonate massif to the northwest were by now subaerially exposed, weathering, and eroding. Furthermore all subsequent Tertiary deposition in the Gulf of Mexico took place basinward of the Balcones/Ouachita Downwarp.

Independent Depth of Burial Conclusions

At the end of the Eocene, thickness of the combined Upper Cretaceous, Paleocene, and Eocene formations covering the Eagle Ford Formation at Austin was a little less than 3000 feet, consistent with depth of burial estimates based on Tmax of immature Eagle Ford samples (Figs. 26 and 27). Over the axis of the San Marcos Arch, it was perhaps 400–600 feet less.

Depth of burial over the central Llano Dome was about 1000 feet; farther northwest, over the San Marcos Arch in the future western Edwards Plateau, the Edwards Group was never covered by more than about 600 feet of younger strata, those being Upper Cretaceous and possibly lower Paleocene (Fig. 28). These estimates are consistent with the absence of stylolites in Edwards and Buda limestones of the Edwards Plateau.

Balcones Faulting (Oligocene-Miocene)

Beginning in early Oligocene (Catahoula Formation) and accelerating through the early and middle Miocene (Oakville Formation), accumulating tectonic stress from gulfward downwarping began to be relieved by normal faulting along the Balcones Fault Zone, probably focused over the Ouachita Overthrust as a zone of pre-existing weakness. The effect of this was that the Hill Country/Llano Uplift/Edwards Plateau block moved up by 1200 feet to more than 1600 feet in the San Antonio–Austin sector (Fig. 29), with gradually decreasing net fault displacements laterally, to west and north. On the south side of the Llano Uplift, the Medina Arch was uplifted more than 300 feet, generating north dip toward the Llano Dome (Fig. 6).

The Oligocene-Miocene coastal plain remained at its previous low-lying coastal level. In response to the abrupt uplift, severe subaerial erosion of the new highlands began building wide alluvial fans on the late Oligocene and Miocene coastal plains outward from the fault scarps (Fig. 30). These fan deposits contained clasts and eroded fossils, first from Austin and Taylor outcrops, followed by lithoclasts, eroded fossils, and chert pebbles derived from the Georgetown and Edwards across a wide swath of coastal plain, from the Brazos to the Nueces River, corresponding to the zone of greatest fault displacement. Balcones faulting probably ended before Pliocene time.

Evolution of Hill Country and Edwards Plateau Landscape

The main streams that now drain the Edwards Plateau (Colorado, Concho, San Saba, Llano, Pedernales, Guadalupe, Medina/San Antonio, Frio, Nueces, and Devils rivers) were probably emplaced as early as late Campanian-Maastrichtian or early Paleocene, and entrenched during Balcones Uplift. Main evidence for this conclusion derives from (1) the principle that meanders form in low-gradient streams flowing in soft sedimentary material, (2) what formations represent the occurrence of such soft sediment and very low gradients, and (3) the distribution of incised meanders around the peripheral margins of the Edwards Plateau.

The characteristic present-day pattern of peripheral spring-fed streams draining radially outward from the Plateau has probably existed since the Miocene, when rainwater accumulating in the basal Edwards formed the widespread, unconfined Plateau Aquifer, charging springs that emerged in canyons cut by headward erosion. Such peripheral canyons, their attendant headwater springs, and outflowing streams and rivers almost certainly have migrated steadily westward from the north-trending Balcones Fault Zone in the San Antonio–Waco sector, and northward from the west-trending fault zone between San Antonio and Del Rio. Thus it should be expected that the ragged eastern and southern margins of the Plateau will continue their westward and northward retreat until the remaining mass of the Edwards Plateau is consumed by erosion during the next 15–25 million years.

Volume of Rock Removed by Post-Balcones Erosion

Today's Edwards Plateau/Llano Uplift/Hill Country landscape indicates substantial removal of rock material by stream erosion cutting headward from Balcones Fault scarps around the eastern and southern margins (Fig. 1). Because of widespread weathering and karstification, it is also probable that much carbonate rock has been carried away in solution. Some weathering, solution, and erosion may also have transpired during the late Cretaceous and early Tertiary, when the Central Texas Platform was first exposed.

Using the formation thickness projections suggested herein, an estimated 8000 cubic miles of rock material has been removed by erosion and dissolution from the Edwards Plateau/Llano Uplift/Hill Country region (Fig. 30)[5]. This removal began about 70 million years ago during the Maastrichtian, continuing at a low level during the Paleocene and Eocene, increasing sharply during Balcones faulting, reaching its maximum about 20 million years ago during early Miocene, continuing through the Pliocene and probably declining somewhat to the present day.

Also removed by post-Balcones erosion were approximately 1300 cubic miles of Upper Cretaceous, Paleocene, and Eocene sediments that had been uplifted along the gulfward front of the Balcones Fault Zone (Fig. 30), where fault displacement was greatest, becoming thinner and narrower to the west as displacements declined (toward Uvalde) and north (toward Waco).

As a way of putting the 8000 cubic miles figure into geological perspective, in the 46,600 square miles of the western Edwards Plateau area (excluding Edwards rocks west of the Pecos

[5]Rock volume removed from the Edwards Plateau was estimated by: (1) enclosing all the area west and north of the Balcones Fault Zone, from Waco to Del Rio, east of the Pecos River and south of Edwards outcrops on the Callahan Divide in an irregular hexagon; (2) estimating the thickness of removed overburden in about 50 evenly scattered locations across that enclosed area; (3) dividing the enclosed area into four triangles; (4) calculating the area of the triangles; (5) averaging the removed values in each triangle; and (6) summing the removed volumes for all four triangles (= 7974 cubic miles). The area of uplifted Upper Cretaceous, Paleocene, and Eocene sediments between the Balcones Fault Zone and the present Oligocene outcrop was represented as a crescent-shaped wedge covering about 5760 square miles, and thinning regularly gulfward from about 1600 feet in the San Antonio–New Braunfels sector, and laterally northward and westward along strike to zero. The volume of eroded sediment in this crescent-shaped wedge was estimated at about 1300 cubic miles.

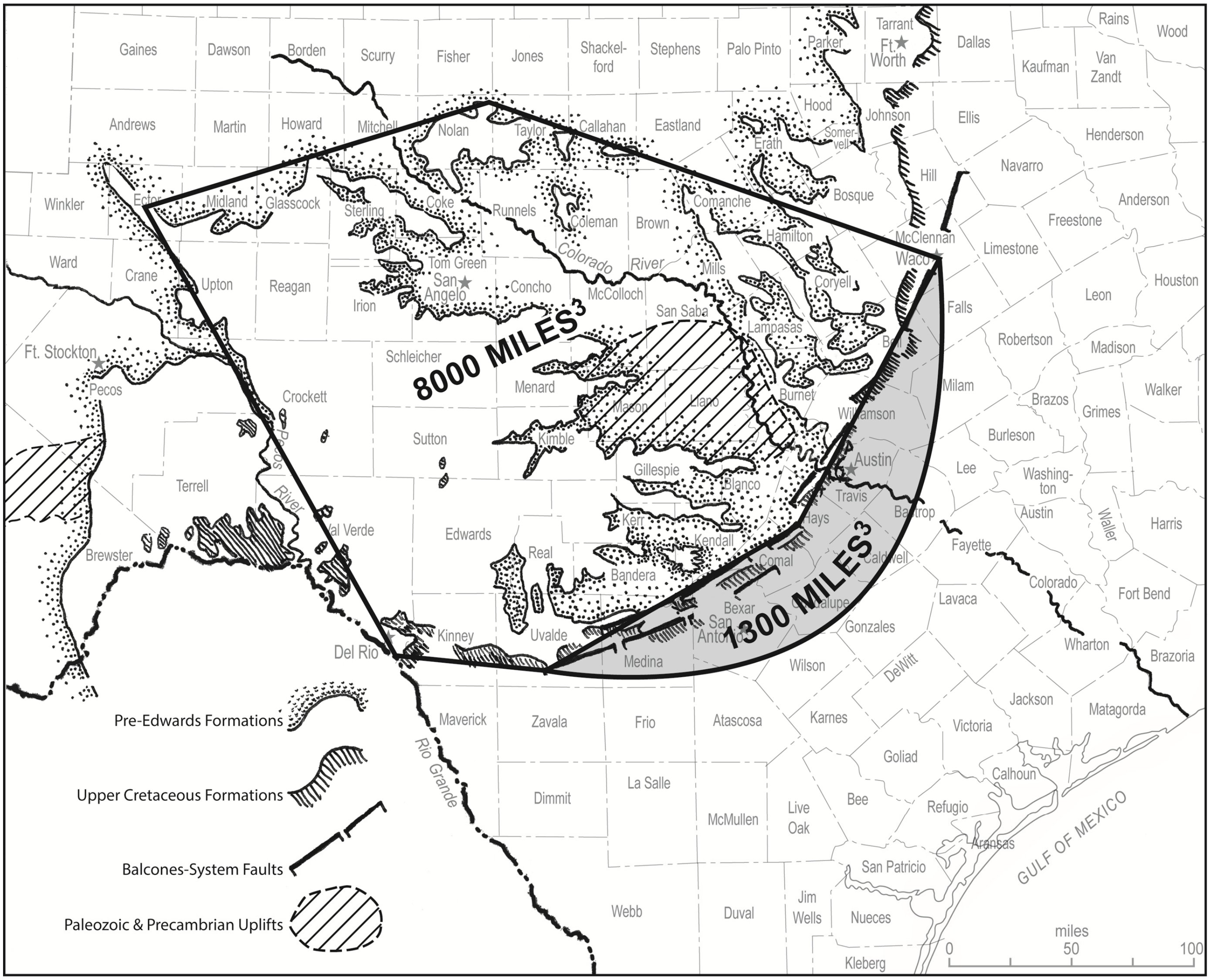


Figure 30. Estimated volumes of rock removed by Tertiary erosion from Edwards Plateau region and Balcones Fault Zone area; shaded area shows arcuate wedge of Upper Cretaceous, Paleocene, and Eocene sediments that were uplifted along gulfward front of the Balcones Fault Zone.

River, which were affected by Laramide uplift adjacent to the Marathon Dome), 28,400 square miles (60%) is covered by outcrops of the Edwards Group and Buda Limestone. In other words, 40% of the area originally covered by the Edwards Plateau has been removed by erosion over the past 20 million years. Keeping in mind that greater thicknesses of rock formations were originally present in the east and south, we may estimate that at least 50% of the volume of rocks that existed west and north of the Balcones Fault Zone at the end of the Eocene has been removed during that period.

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I thank all these friends for their suggestions; any errors of fact or omission are, however, entirely my own responsibility.

My friend Dennis Trombatore, distinguished Librarian of the Walter Geological Library at the Jackson School of Geoscience, University of Texas (Austin) was knowledgeable and tireless in helping me locate obscure sources—many thanks, Dennis!

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